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16. Abstract <p>This document provides a comprehensive, state-of-the-art review of the operation and control strategies of light rail transit systems. It is intended to serve as a basis for further research in the goals of developing an analytical tool for evaluating the operations of light rail at-grade within an urban signal system. The report identifies the various at-grade crossing types that can exist for a light rail transit system, the operating characteristics of light rail vehicles, and the use of control devices at at-grade crossings. The intent of the report is also to summarize both the priority strategies used by transit agencies and the methods of evaluation used to assess the impacts of light rail transit systems. Simulation has been proposed as a method of analysis; therefore, a summary describing the operation of three applicable computer simulation packages is provided.</p> <p>An appendix of this document provides the minutes of both the technical and steering committee meetings for the project. The minutes are an integral part of the project and have had a significant impact on the study focus, especially in avoiding the duplication of research effort.</p>					
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DEVELOPMENT OF ANALYTICAL TOOLS FOR EVALUATING OPERATIONS OF LIGHT-RAIL AT-GRADE WITHIN AN URBAN SIGNAL SYSTEM

INTERIM REPORT

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Study Title: Development of Analytical Tools For Evaluating
Operations of Light-Rail At Grade Within An Urban Signal System**

**Sponsored by the
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and the Federal Highway Administration**

March 1993

**TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135**

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					LENGTH				
in	Inches	2.54	centimeters	cm	mm	millimeters	0.039	Inches	in
ft	feet	0.3048	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	yd	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
AREA					AREA				
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ac	acres	0.395	hectares	ha					
MASS (weight)					MASS (weight)				
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lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams (1000 kg)	1.103	short tons	T
VOLUME					VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft ³	cubic feet	0.0328	meters cubed	m ³	m ³	meters cubed	35.315	cubic feet	ft ³
yd ³	cubic yards	0.765	meters cubed	m ³	m ³	meters cubed	1.308	cubic yards	yd ³
Note: Volumes greater than 1000 L shall be shown in m ³ .									
TEMPERATURE (exact)					TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C	°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
<p>These factors conform to the requirement of FHWA Order 5190.1A</p> <p>*SI is the symbol for the International System of Measurements</p>									

IMPLEMENTATION STATEMENT

The following interim report contains the literature review and the minutes of the meetings with the project steering and technical committees that were conducted to develop an analytical tool for evaluating light rail transit (LRT) operations at-grade within an urban signal system. Research to date has focused attention on the Federal Highway Administration's NETSIM as the program capable of simulating and providing measures of effectiveness to describe arterial street and light rail transit operations.

The next phases of the project will include a data collection and the use of this data to test the selected methodologies (including NETSIM). Data will be collected from cities with existing LRT in operation. The most accurate and appropriate methodology or methodologies will be selected and assembled into a final methodology, which will then be fully developed and calibrated for LRT evaluation in a signalized network. The resulting methodology will be computerized and may consist of several simulation and/or optimization software packages. Therefore, a reference guide for the use of the methodology will be incorporated into the final report provided at the conclusion of the study.

The completed research, of which this interim report forms a part, will provide engineers with a methodology and computerized procedure for assessing the impacts of an LRT system on a signalized urban arterial street network. Through analyzing various configurations of roadway and trackage geometrics and signalization alternatives, the engineer can make decisions for the optimum LRT placement and signal operations in an efficient and organized fashion.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration, the Texas Department of Transportation, or the Texas Transportation Institute. This report does not constitute a standard, specification, or regulation and is **NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.**

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The authors wish to thank the following individuals for serving on the advisory panel (steering committee) for this project:

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Donald R. Garrison	TxDOT, Houston District
David G. Gerard	City of Austin
John P. Kelly	TxDOT, Dallas District
Rich Krisak	Dallas Area Rapid Transit (DART)
Ernie Martinez	Capital Metro, Austin
Jim Robertson	Capital Metro, Austin
John Sedlack	METRO, Houston

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Kenneth W. Ogden	Monash University, Australia
Robert N. Wunderlich	Barton-Aschman, Associates, Inc.

Special thanks are given to Kenneth W. Ogden for his time in presenting the technical committee with a presentation on the LRT system in Melbourne, Australia.

Names, work addresses and work phone numbers of all steering and technical committee members are provided in the appendix of this report.

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SUMMARY

As light rail transit becomes an increasingly popular transit alternative, there is a need of cities in the planning and development stages to make informed decisions about the optimum signal system operation, potential locations for grade separation, and other mitigation measures. It is the intent of this effort to provide these agencies a useful and comprehensible tool for the evaluation of light rail transit (LRT) alternatives. To accomplish this goal, the objective of this study is the development of a procedure for better assessing the impacts of light rail at-grade operations on an urban signal system.

A state-of-the-art review was conducted to identify current methods and techniques for assessing the impacts of at-grade LRT operation on an urban street network. Additionally, an advisory panel was assembled to provide direction to the study effort and to make recommendations to ensure that the finished procedure is applicable and utilitarian in evaluating LRT alternatives. Methodologies described in the literature as well as those used by transit agencies to plan, implement, and coordinate LRT operations were collected and examined for their application to the current network study.

This document provides a comprehensive, state-of-the-art review of the operation and control strategies of light rail transit systems. It is intended to serve as a basis for further research in the goals of developing an analytical tool for evaluating operations of light rail at-grade within an urban signal system. The report identifies the various at-grade crossing types that can exist for an LRT system, the operating characteristics of light rail vehicles, and the use of control devices at at-grade crossings. The intent of the report is also to summarize both the priority strategies presently used by transit agencies and the methods of evaluation used to assess the impacts of LRT systems. The use of simulation has been proposed as a method of analysis; therefore, a summary describing the operation of three applicable microcomputer simulation packages is provided.

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INTRODUCTION

This report documents the findings of a literature review for Texas Highway Planning and Research (HPR) Study Number 2-11-92/4-1278: "Development of Analytical Tools for Evaluating Operations of Light Rail At-Grade within an Urban Signal System." The information synthesized from over sixty articles included the theoretical aspects of at-grade light rail transit (LRT) implementation and the system characteristics of operating LRT networks in cities in the United States, Canada, and Australia. Attention was focused on LRT-roadway crossings. The principal engineering concerns at these intersections are the location of the LRT trackage with respect to the roadway, the use and operation of traffic control devices, the degree and flexibility of preemption provided for LRT, and the method of evaluating the impacts at the intersection.

PROBLEM STATEMENT

As LRT becomes an increasingly popular transit alternative, there is a need of cities in the planning and development stages to make informed decisions about the optimum signal system operation. Integrating the LRT system into the existing urban signal system has created a need to better analyze the effects of the LRT system on the traffic signalization as well as the effects of the signalization on train operations. Research has been done to develop analytical tools to simulate the operations of signal systems in a network, but as yet no definitive method exists for the inclusion of light rail at-grade crossings within such a network. The goal of this study is to develop an analytical tool or methodology to assist in the decision making of the operations of LRT, and to determine when grade separation and other mitigation measures are appropriate.

PROJECT BACKGROUND

LRT is being considered by several cities within the state of Texas. Both Dallas and Houston are currently moving forward with the planning and development of LRT systems. In addition, Austin has recently initiated a re-examination of rail transit alternatives and El Paso is starting to explore rail transit options. To minimize costs and to maximize the flexibility of LRT, at-grade operation is being considered.

The primary benefit to be realized from this research is a standard methodology for evaluation of operation of light rail at-grade crossings within a signalized network. With such a tool, transit authorities and the cities involved would be better able to identify locations where at-grade operation presents a high potential for traffic disruption. In addition, alternative mitigation measures, signalization schemes, roadway improvements or the impacts of selected grade separations could be easily tested.

OBJECTIVES

The objectives of the study are as follows:

1. Assemble an advisory panel to guide the study;
2. Contact transit agencies and cities with light rail systems to obtain and compare analytical methodologies and/or models;
3. Select a representative sample of study cities & obtain operational data;
4. Compare the predicted operations for these systems, using the models or analytical methodologies, with observed operations in the study cities;
5. Refine the most reliable existing model or analytical methodology to test variable operating parameters for light rail and under various traffic operations and control strategies;
6. Test and calibrate the resulting methodology using data from the study cities; and
7. Develop a reference guide with operational evaluation procedures.

WORK PLAN

The proposed work plan consists of eight tasks necessary for completing the above objectives. These tasks are listed below:

1. State-of-the-Art Review;
2. Assemble Advisor Panel;
3. Collect and Evaluate Methodologies Used by Other Agencies;
4. Observe Operation of Existing Facilities;
5. Test Selected Theoretical Methodologies Against Operational Data;
6. Develop and Calibrate Evaluation Methodology;
7. Develop Computerized Analytical Tool and Reference Guide; and
8. Prepare Final Report.

RESEARCH ACTIVITY TO DATE

Table 1 summarizes the status (completed, on-going, or planned) of the study objectives and associated tasks. The advisory panels - a steering committee and a technical committee - have been assembled and communicated with on a scheduled basis. The committee members have been listed in the acknowledgements section of this report and their work addresses and phone numbers are provided in Appendix A of the report. Minutes for all meetings with the steering and technical committees have also been included and are located in Appendix B.

In the process of collecting and reviewing the information in the literature pertaining to LRT, it was discovered that most analytical methods were theoretical, general in nature, or applicable only to isolated intersections of roadways and LRT lines. Based on the information that could be drawn from the review and the recommendations of the steering committee, the focus of continued study in developing a final methodology will consist of the microcomputer transportation programs TRANSYT-7F, PASSER II, and NETSIM. These software packages will be used independently or in conjunction with one another,

Table 1. Schedule of Research Activities

RESEARCH ACTIVITY		ACTIVITY STATUS
Objective 1: -Task 2-	Assemble Advisory Panel Communicate with Panel	COMPLETED ON-GOING
Objective 2: -Task 1- -Task 3-	Collect and analyze evaluation methodologies State-of-the-art Review Collect and analyze methodologies	COMPLETED COMPLETED COMPLETED
Objective 3: -Task 4-	Select and observe existing facilities Observe existing facilities	ON-GOING ON-GOING
Objective 4: -Task 5-	Compare predicted results to field data Test candidate methodologies	ON-GOING ON-GOING
Objective 5: -Task 5-	Select and fine tune preferred methodology Test candidate methodologies	ON-GOING ON-GOING
Objective 6: -Task 6- -Task 7-	Test and calibrate selected methodology Develop and calibrate methodology Develop computerized analysis tool	PLANNED PLANNED PLANNED
Objective 7: -Task 8-	Develop reference guide for methodology Prepare final report	PLANNED PLANNED

depending on the type and the intensity of the network being analyzed. The compatibility between the programs used for the analysis and the type of network being analyzed is currently being evaluated in Task 5.

The literature review of this report represents the completion of Tasks 1 and 3 of the tasks listed above. This document provides a comprehensive review of the operation and control strategies of LRT systems. It is intended to provide a basis for further research in the goal of developing an analytical tool for evaluating operations of light rail at-grade within an urban signal system. The report identifies the various at-grade crossing types that can exist for an LRT system, the operating characteristics of light rail vehicles, and the use of control devices at at-grade crossings. The intent of the report was also to summarize both the preemption strategies presently used by transit agencies and the methods of evaluation used to assess the impacts of LRT systems. The use of simulation has been proposed as a method of analysis; therefore, a summary describing the operation of three applicable microcomputer simulation packages is provided.

Some cities with operating LRT systems have been visited, but at the time of this report no final decision has been made as to what cities should be used for the data collection that will be used to calibrate and test the developed methodology. Current recommendations center around cities that most resemble Texas cities in their land use and transportation systems. Preliminary suggestions have included Calgary (a city already visited), Portland, Los Angeles-Long Beach, and San Diego.

Any further recommendations by persons reading this report are welcome and may be communicated to the authors of this report (addresses and phone numbers are located in Appendix A).

COMPREHENSIVE LITERATURE REVIEW

The literature review for this project included over sixty articles from sources within and outside of the United States. In addition, cities with existing light rail transit systems were contacted to obtain information on how the at-grade LRT intersections operate and how the efficiency of the system is assessed. This review summarizes the findings of the article review and the city contacts. The focus of the information presented is a general overview of: the location of the LRT trackage with respect to the roadway, the use and operation of traffic control devices, the degree and flexibility of preemption provided for LRT, and the method of evaluating the impacts at the intersection.

CROSSING CONFIGURATIONS AND THE LRT PHYSICAL ENVIRONMENT

Berry [2] has identified four major at-grade configurations that exist for LRT-roadway intersections. A description of these crossings is included here as a means of introducing uniform terminology. Additional information has been provided, where appropriate, to establish lines of differentiation between the categories and visual outlays of the crossing types have been provided in Figure 1. For adjacent and median crossings, "mid-block" considerations have been included in the discussion. Finally, LRT right-of-way and other aspects of the LRT operating environment are described.

Isolated LRT Crossing

An isolated LRT crossing is one at which there is no nearby traffic control device and the intersection is unaffected by any intersections or conflicting flows(Figure 1A). At such a crossing, the sole effect of a crossing train is delay to automobiles attempting to cross the tracks. Cline, et al [27] used a computer simulation program (NETSIM) with the LRT's vehicle characteristics coded as inputs to determine that a crossing is isolated if it is located greater than 400 feet from a traffic control device. No delay was imposed on the Light Rail Vehicle (LRV) from automobiles crossing the tracks - no queue effects were caused by an upstream traffic control device. Berry [2] indicates that the measure of effectiveness for evaluating level of service at such a crossing is the average individual stopped delay per vehicle.

Isolated LRT Crossing - nearby traffic control device

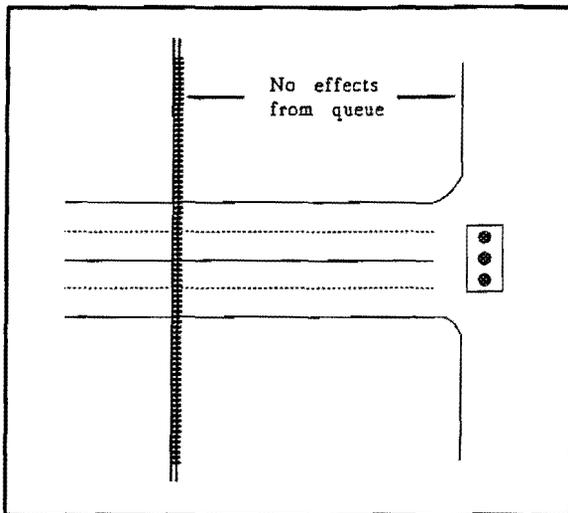
Given the above criteria for a completely isolated crossing, an isolated crossing is considered to have a "nearby" traffic control device when that device is located within 400

feet of the LRT intersection on the crossing roadway (Figure 1B). This case encompasses all crossings between the isolated crossing and the case where the LRV runs adjacent to a parallel street. In the case where the LRV trackage is close to a parallel roadway, the queue at the traffic control device may extend over the LRT tracks and delay the LRV. Automobile delay can occur in two ways: (1) vehicles stopped to wait for a crossing LRV may have to stop and queue up again at the nearby traffic control device after crossing the tracks; and (2) vehicles stopped on the nearside of the roadway for an LRV may be queued in large enough quantity to "spillback" into the intersection controlled by the traffic control device. At intersections with high traffic volumes, the traffic control device at the isolated crossing should be integrated with the "nearby" traffic control device for improved safety and level of service. One measure of effectiveness for evaluating the level of service at this crossing type is the average individual stopped delay per vehicle. The measure of effectiveness (MOE) for evaluating the crossing roadway's level of service is average travel speed (Berry [2]).

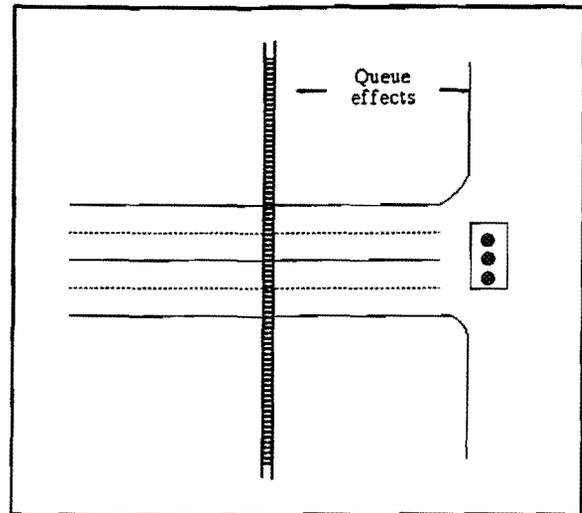
Crossings Adjacent to Parallel Street

A third type of LRT-roadway intersection is a crossing where the LRT trackage is adjacent to a parallel street (Figure 1C). The tracks can be located in a separate right-of-way (ROW) adjacent to the street or in a shared ROW with the roadway. With reference to the latter condition, this classification of crossing also includes the case where the LRV operates in mixed traffic with automobiles. Principal concerns at this type of crossing include: the presence and handling of turning automobiles - especially autos turning right across the LRT tracks; the need to prevent vehicles on the cross street from encroaching on the LRT tracks; the degree of priority that should be provided for LRVs; signal timing for minimal delay to automobiles and LRV passengers; the effects of altering the signal timing for an LRV when the signal is timed for automobile progression; and the handling of boarding and alighting passengers from the LRV (especially for the special case of mixed traffic operation). Typical MOE's for this crossing type include the delay to automobiles, the delay to LRV patrons, and the volume to capacity ratio at the intersection.

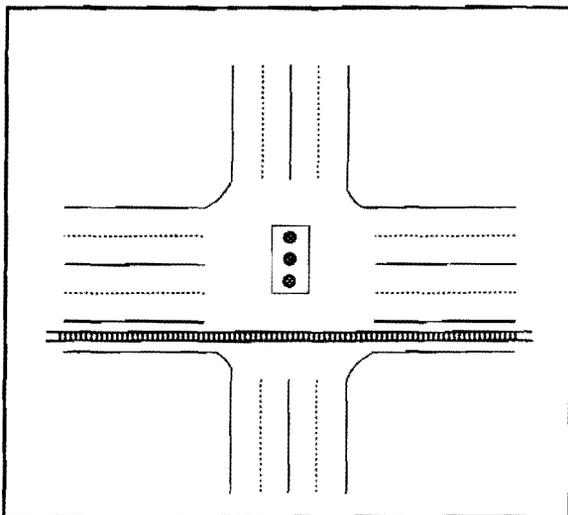
Side of street LRT operation describes the situation where LRVs operate to the right of the nearest automobile under two-way adjacent parallel street operation. ITE 6Y-37 [8] indicates that where there would be frequent crossings with minor streets and driveways, side of street running should be avoided. If side of street operation is necessary, these crossings should be eliminated or controlled directly. Right turns into such driveways and/or minor streets across the LRT tracks should be prohibited or directly controlled due to the driver's limited sight distance in perceiving an LRV approaching the driveway/street when travelling in the same direction.



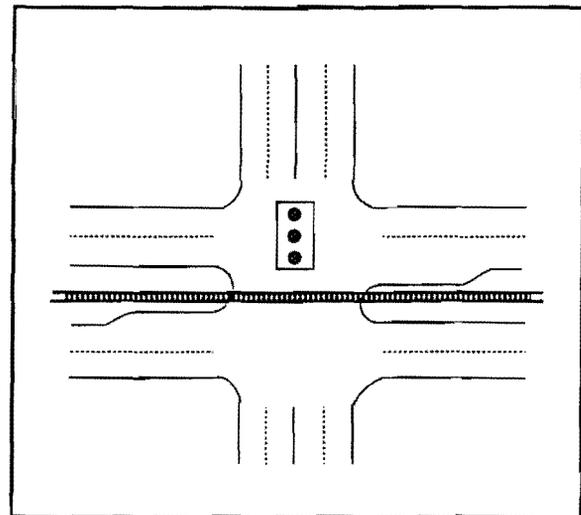
A. Isolated Crossing



B. Isolated Crossing near signal



C. Crossing Adjacent to Parallel Street



D. Crossing for LRT Median Operation

Figure 1. Types of LRT Crossings

Crossings for LRT Median Operation

Crossings where the LRT runs in the median of the roadway constitute the final LRT crossing classification (Figure 1D). The LRT trackage should be located at roadway elevation to avoid a raised RR track "bump" over which automobiles must pass in negotiating the intersection. Issues present at this crossing include: the handling of left turning vehicles on the street whose median the LRV is occupying; the degree of priority that should be provided for the LRV; signal timing for minimal delay to automobiles and LRV passengers; the effects of altering the signal timing for an LRV when the signal is timed for automobile progression; and the safety provisions for passengers boarding or alighting from the LRV. Possible solutions to some of these issues include the elimination of left turns except at selected crossings (Woodward corridor in Detroit, Tighe and Patterson [13]) and the use of a special signal phase for the LRV. The provision of direct control over left turns and U-turns on the parallel roadway is also supported in ITE 6Y-37 [8]. Similar to adjacent LRV running, the common measures of effectiveness for this intersection include delay to automobiles, delay to LRV patrons, and the v/c ratio at the intersection.

Median of a street LRT operation indicates the presence of the trackage in the median of the arterial. If a wide median already exists in the arterial, the major advantages to this track location are the presence of existing ROW and partial horizontal separation from street traffic. For safe and efficient operation, it is recommended (ITE 6Y-37 [8]) that left turns and U-turns from the parallel roadway be prohibited at all mid-block locations. A presentation of LRT median implementation can be found in Tighe and Patterson [13]. LRT passenger handling is an important issue in median operation, and usually involves pedestrian phases incorporated into the intersection signal phasing.

LRT Right-of-way and Physical Environment

Varying at-grade LRT track placements have been utilized in cities around the globe. Despite this diversity, five general classes of track locations define and classify a vast majority of these placements. Ranging from least to greatest interaction with automobile traffic, these locations are: grade separation, exclusive right-of-way, side of street, median of street, and mixed traffic. Grade separation is included in this discussion as there are many predominantly at-grade LRT lines that are grade separated at intersections where a high degree of automobile congestion exists. The information for track locations is provided in addition to the crossing information above and can be considered as supportive information that applies between crossings (i.e. "mid-block" considerations).

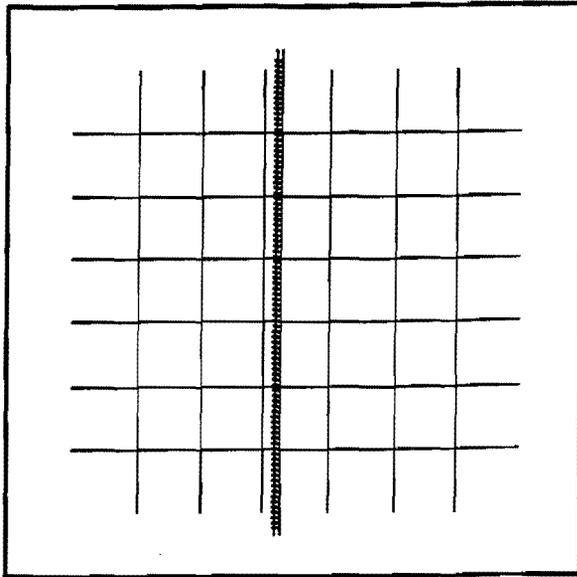
Grade separation is the physical raising or lowering of the LRT tracks to create an "overpass" at an intersection or an intersecting roadway. This practice is avoided in LRT planning due to its high capital expense, space requirements, and failure to utilize the flexibility of the LRT mode. Grade separation, however, may be a "necessary evil" in

situations where the at-grade presence of an LRV imposes delay to motorists that when translated into dollar expense for vehicle fuel costs, time spent delayed in traffic and vehicle emissions, exceeds the cost of the grade separation. Economic criteria for grade separation of LRT tracks have been developed by Cline, et al [21,22], and roadway volumetric criteria for grade separation have been developed by Bates and Lee [1] and ITE Committee 6Y-37 [8]. Bates and Lee state that separation should be seriously considered when traffic volumes exceed 30,000 ADT. In situations where cross street traffic volume is between 20,000 and 30,000 ADT, separation may be necessary if the LRT is to operate at full priority. ITE 6Y-37 indicates that grade separation should be considered with traffic volumes greater than 30,000 to 40,000 ADT and LRT headways of 3-6 minutes.

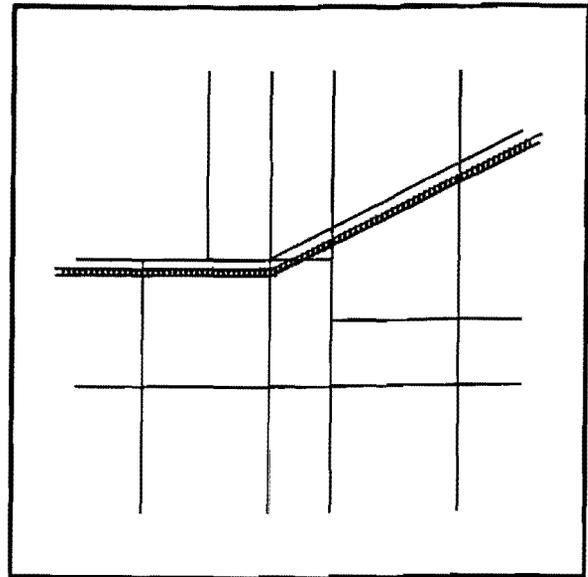
Exclusive right-of-way defines the case where LRT track is located on property reserved for the passage of LRV's. Property acquisition is often very expensive, so exclusive ROW for LRT occurs where the governing agency is committed to its LRT system or where abandoned railway or highway ROW exists. A condition of exclusive ROW in the LRT arena is the provision that there are no mid-block auto crossings of the LRT tracks. Only at major crossings is there a physical interaction between the autos and LRV's. Thus, the major concerns of exclusive ROW running surround the operations at intersections. The use of exclusive ROW for LRT running is not always feasible or desirable. Alternatively, the LRT system could run in a shared ROW with an operating railroad using separate or shared rail from freight rail or heavy rail transit. An example of the benefits and problems associated with locating an LRT line in an existing rail corridor is found in the Los Angeles experience discussed by McSpedon [30]. Where two or more transportation modes operate within a segment of right-of-way, the situation is termed "shared right-of-way." When the modes are separated by barriers, land strips, curbs or painted markings, the term "horizontal separation," or "semi-exclusive ROW," describes these configurations.

Mixed traffic running is the final at-grade location for LRT trackage. The tracks are physically located in the street pavement and are level with the pavement surface. The LRV operates much like a bus in mixed traffic with automobiles. One advantage of this track location is that no ROW acquisition is necessary, and control by existing traffic signals and signs would be required, although detector equipment and advanced signal controllers would be required if LRV priority is deemed necessary. Disadvantages to this operation include adverse impacts on roadway capacity, reduced average speeds from LRV station stops and variability in arrival times due to the unpredictability of street traffic. Considerations for mixed traffic running can be found in Wilkins and Boscia [25].

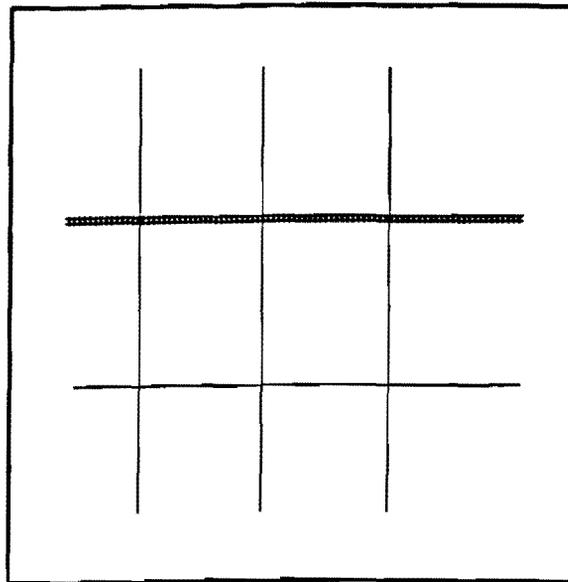
Definable urban environments exist in which any number of combinations of the crossing types identified above can be found. The environments themselves usually exist in combination with one another and in varying succession along the LRT line. Figure 2 depicts the major urban environments as: (1) LRT in grid network; (2) "downtown" system; and (3) widely spaced arterials. In the tight grid network, the LRT line would encounter arterials and minor streets at even distances (or multiples of a grid distance). Space is likely



A. LRT in Grid Network



B. "Downtown" System



C. Widely Spaced Arterials

Figure 2. LRT Urban Environments

to be limited in the corridors, and signal timing should be designed so that the LRVs run without a major impact on the adjacent street progression. In the "downtown" environment, the LRV can expect to encounter curved streets, one-way streets, pedestrian malls and/or smaller streets (and driveways) along the line. Where the LRV will cross widely spaced arterials, crossing arterials will be impacted by the presence of the LRV through lower average travel speeds, but parallel arterials should not be directly affected.

LRT OPERATIONS

The physical description, performance characteristics and operating parameters of LRVs including LRV headway, dwell time, operating speed and blockage time at LRT-roadway intersections will be addressed in this section.

Vehicle Characteristics

Modern LRVs are enclosed, trolley-like vehicles that are direct descendants of the PCC cars of the 1930's. Motive power is obtained from overhead electric catenary that is grounded by the dual guideway rails. Unlike "heavy rail" transit, there exists no "third" rail for electric power near the ground surface, making LRT safer in pedestrian environments. LRT is also differentiable from "commuter rail," which uses internally generated power through deisel generated electric power or diesel fuel. The LRT's catenary can, in advanced systems, also be used as a two-way communication media with a central controller. Another defining characteristic of LRT is its boarding flexibility using low to medium height platforms. LRVs may operate singly or in short trains of up to five vehicles, though three vehicle trains are more common. Table 2 below shows typical LRV operating parameters and dimensions compiled by Larwin and Rosenberg [32] in 1978.

Table 2. LRV Characteristics

CHARACTERISTIC	VALUE
Acceleration	2 mph/s
Deceleration	3 mph/s
Maximum Braking Rate	4 mph/s
Emergency Braking Rate	6 mph/s
Number of Articulations	0, 1, or 2
Length	60 - 90 feet
Width	7.9 - 9.3 feet
Turning Radius	42 - 82 feet

Headways

Headway refers to the time elapsed between successive arrivals of same-direction LRVs. For LRT systems not running on a strict pre-timed basis, headways are subject to variability caused by driver and vehicle performance differences, varying boarding/alighting demands by passengers and interaction with other modes of transportation (especially automobiles in a mixed traffic scenario). A study of the effects of increased scheduled LRV headway on automobile delay was conducted by Cline et al [21,22]. The findings indicate that decreased headways (increased train frequency) will increase automobile delay, and that this effect becomes more pronounced as automobile volumes increase. When viewed as reasonably consistent successive events, LRV headways adopt a cyclical pattern. For one-way LRV operation, this cycle can be incorporated in a variety of fashions into the signal timing at roadway intersections to allow optimum flows of motor vehicles and LRVs. Most LRT operations, however, use LRVs in two-way passage. This complicates the signal timing requirements at the intersection in that two independent LRVs are approaching the intersection at different times (same time arrivals would be only due to random chance or adherence to a strict pre-timed schedule), from different directions, and at different headways (though headways may be the same if there is no "peak" direction). Assessment of the impacts of two-way LRV operation on a street network is an objective of the present study.

Dwell Time

Dwell time is the time elapsed while an LRV remains stationary at a station stop. Minimum and maximum station dwell times are set by the transit agency. Ideally, the dwell time should be great enough for all departing passengers to alight and all arriving passengers to board; however, in order to adhere to a schedule or remain within a fixed - time progression band, an LRV may be required to leave before boarding/alighting has been completed. Departure alarms or bells should prove sufficient warning to passengers in this instance. Depending on the priority strategy provided for the LRV, a longer or shorter than expected dwell time could affect the upstream progression of the LRV (the LRV may be too early or late for a "green" signal). Special priority systems can be implemented where the LRV operator signals the controller when the LRV is ready for departure, and the controller preempts the traffic signals to provide a green band for the LRV to the next station. Alternatively, an LRV dwelling at the station may receive a departure signal when it can accelerate and conform to a pre-timed signal scheme.

Operating Speed

The speed of an LRV will vary depending on its operating environment. The maximum speeds are often limited for safety reasons to 55 mph in exclusive ROW. In

mixed traffic operation, LRV speeds are limited to the progression speed of the automobiles sharing the roadway. Transit agencies set limits on speeds in pedestrian malls and at LRT-roadway crossings. A safe speed for an LRV in a pedestrian mall could be as low as 5-10 mph. Crossing speeds can safely be higher at gated crossings than at passive sign (crossbuck) protected crossings. Crossing speed information as stated in Reference [8] can be found in Table 3 "LRT System Statistics for Selected Cities".

Blockage Time, Crossing Clearance Time, Lost Time

Blockage time refers to the time that an LRT-roadway intersection is physically blocked by the presence of an LRV. Alternatively, blockage time can be defined as the time the driver responds to an active warning device and the presence of an LRV. Blockage time is considered to end when the LRV has physically crossed the roadway. In multi-LRV trains, the blockage time is higher than for a single LRV, given a constant speed. Crossing clearance time is the time between the physical departure of a crossing LRV and the time when an active warning device ceases operation. Berry and Williams [3] state that at unprotected (passively controlled) LRT crossings, there is no measurable clearance time, and traffic resumes on the cross street when the LRV clears the roadway.

Lost time defines the period between the time when an automobile driver may cross the LRT tracks - after the LRV passes at unprotected crossings, after the active warning device ceases operation at protected crossings - and the time when the driver actually begins to traverse the crossing.

TRAFFIC CONTROL DEVICES

The U.S. Department of Transportation-Association of American Railroads (DOT-AAR) and the Federal Railroad Administration's data files classify warning devices at railroad crossings into eight categories. The first four warning device classes (no signs, other signs, stop signs, and crossbucks) are referred to as passive devices. Classes 5, 6, and 7 (special devices, wigwags or bells, and flashing lights, respectively) have usually been grouped into the flashing light category (active devices). Class 8 of warning devices (flashing lights with gates) represents the most extensive type of protection for railroad crossings [52].

In this study, traffic control devices at at-grade LRT crossings will be grouped into one of four categories: (1)Crossbucks only; (2)Flashing light signals and crossbucks; (3)Flashing light signals, gates and crossbucks; and (4)Standard traffic signals [2]. There is a level of delay associated with each of these traffic control devices. This level of delay is a function of the track geometry, sight distance, station spacing, train protection, parallel traffic speed and type of crossing control. The special operating characteristics of the light

Table 3. LRT System Statistics for Selected Cities

City	Speed at Crossings (mph)	Length (mi.)	Minimum Headway (min)	Roadway At-Grade Crossings	Side	Median	Mixed	Exclusive	Grade Separated
Boston, MA	15-20	26.9	5	67		X	X		X
Buffalo, NY	15	6.4	5	8		X			
Calgary, Can.	25-50	17.6	2.5	44		X		X	X
Cleveland, OH	25-40	13.3	4	21		X			X
Edmonton, Can.	37	7.7	5	11				X	
Los Angeles, CA	varies	22	6	85	X	X		X	
Melbourne, Aus.	varies	206	3	N/A		X	X	X	
New Orleans, LA	10	9.3	4	112	X	X			
Newark, NJ	20	4.5	2	1					X
Philadelphia, PA	30-50	83.65	3	1059			X	X	
Pittsburgh, PA	10-15	29.31	3	46			X	X	
Portland, OR	15-35	15.85	7.5	69	X	X		X	X
Sacramento, CA	35	18	15	85		X	X	X	
San Diego, CA	25-50	31.5	15	79		X		X	
San Francisco, CA	11	21.5	3	197		X	X	X	
San Jose, CA	10-35	20.1	5	51		X	X		
Toronto, Can.	10	48.4	2.5	290			X		

rail vehicle, particularly with regard to braking, also affects the control type used at the LRT crossing [6]. The following provides a discussion of the operation of the intersection under each of these traffic control devices. The section attempts to answer questions regarding when it is appropriate to use a specific traffic control device, the details of how the device is operated, and the potential impacts associated with each type of device.

Crossbucks Alone/ Flashing Light Signals and Crossbucks Crossing

The operation of the intersection under crossbucks alone or under flashing light signals and crossbucks is very similar in its operation and impacts. Intersections controlled by crossbucks only or flashing light signals and crossbucks are typically operated in locations where the crossing volumes and train speeds are low. Vehicles crossing railroad tracks under this traffic control device must stop at the tracks before crossing. These intersections require careful design to ensure that sight distances are adequate and that points of conflict are clearly defined. The successful operation of these intersections is subject to the capacity limitations of stop sign controlled intersections [13].

Flashing Light Signals, Gates, and Crossbucks Crossing

The use of gates at at-grade crossings was initially developed for railroads where trains could not stop for crossings and the train speeds exceeded 35 mph. Gates are generally used at those intersections where traffic signals are ineffective, or where unusual intersection configuration makes traffic signal control unreliable. These gates are actuated by track circuits and require railroad type preemption of any traffic signals at the intersection (or within 200 feet according to California Public Utility Commission standards) in advance of the train's arrival. CPUC standards require this type of traffic control device where the LRV is operating off-street and uninterrupted flow is desired [10].

Although safer than traffic signals, crossing gates have drawbacks. Their operation cycle is slower, so that they increase traffic interference significantly. Increased gate time arises from the actual operating time required to provide warning and lower the gates. There is a regulatory "advanced warning" time (typically 20 sec) required between the lowering of the gate and the arrival of the train. It is also usually physically impractical to construct an adequately gated crossing in the middle of an intersection because of the physical space requirements of the control hardware [6,13].

Gates can also cause additional delays when shortly after a train has left a crossing another train is detected coming from the opposite direction. What results is that the gates lift and lower again in a short sequence. The Canadian National Railway prevents this short sequence between successive gate closures by maintaining a minimum time of ten seconds

between sequential gate closure [55]. Along the Edmonton LRT system, if a train is within 15 seconds of calling the gates down from the opposite direction, the gates will be held down while waiting for the next train [29].

Standard Traffic Signals

The majority of LRT crossings at intersections are controlled by traffic signals. The effectiveness of traffic signals for LRT crossings depends on the intersection configuration and the LRV speed. If the LRT is located in a median, or is side-running in the direction of the adjacent traffic flow, then traffic signals work well. In a setting where preemption is not provided, LRVs are required to stop or proceed in accordance with the signal in exactly the same way as automobile traffic. Under this operation, the LRV approach speed is restricted to a maximum of 35 mph because an LRV may have to stop on short notice when its signal display changes to yellow. This speed results from the deceleration capabilities of LRVs and consideration of the comfort and safety of standing passengers [6, 13].

One of the major advantages of traffic signal control at at-grade intersections is the flexibility available in providing priority. Using traffic signals at at-grade LRT crossings any degree of priority, from none to total preemption, can be given to LRT. The level of priority can also be varied by time of day, and traffic signal coordination can be provided. When unusual street configurations occur, however, signal control is less effective [6, 13].

PREEMPTION

Signal preemption or signal priority is an attempt to minimize or eliminate LRV delay by temporarily altering the traffic signal phase so that an approaching LRV receives a green phase when it arrives. Piper, et al [34] provides an extensive discussion on priority techniques. The traffic signal priority treatments outlined in that report were subdivided into passive and active priority treatments. Passive priority treatments use anticipated public transit operations to determine the required priority treatment to be implemented. The following lists several treatments that fall under this category:

1. Reduced cycle time;
2. Priority movement repetition in the cycle;
3. Green allocation weighed towards the priority movement;
4. Phasing design; and
5. Linking of signals for tram progression.

Active priority improves upon one basic weakness in passive priority treatments, and that is its ability to sense the presence of the public transit vehicle and to select the most suitable priority technique. The following list shows treatments that fall under this category:

1. Phase extension;
2. Phase early start;
3. Special phase;
4. Phase suppression;
5. Priority phase sequences;
6. Compensation; and
7. Flexible window stretching.

Controller Types

The microprocessor traffic signal controller is one means of implementing a flexible and low-cost system of controlling light rail vehicles and providing preemption at signalized intersections. Before discussing the preemption of traffic signal controllers, it is first necessary to understand the nature of traffic controllers. Reference [20] summarizes the preemption capabilities of a number of currently used traffic signal controllers and identifies shortcomings in the preemption logic of these controllers. Although this reference deals with preemption in terms of railroad preemption, the information provided can be useful when discussing preemption for LRT trains.

There are two general types of actuated traffic signal controllers available: Type 170 models and units based on the National Electrical Manufacturers Association (NEMA) standard. Type 170 controllers can theoretically be operated in a variety of ways. NEMA, on the other hand, is limited to the factory-set configurations and capabilities. All controllers reviewed in this document provide the same basic preemption sequencing [20]:

1. Entry into preemption;
2. Termination of the phase in operation;
3. Track clearance phase;
4. Hold interval; and
5. Return to normal operation.

Preemption Schemes in Selected Cities

The following provides a brief description of the preemption techniques used by various LRT systems. Systems with no signal preemption include: Boston, Cleveland (no preemption at some of the signals), Newark, New Orleans, Philadelphia, Pittsburgh, and San Francisco. Tables 4 and 5 also summarize the operating priorities and characteristics for various LRT systems.

Table 4. Operating Priorities for At-Grade LRT Crossings

LRV Loc.->	Side	Median	Mixed Traffic	Exclusive
LRV Full Priority	Portland	Buffalo	Melbourne	Calgary
		Calgary		Edmonton
		San Diego		Sacramento
		Melbourne		San Diego
Traffic Priority	New Orleans			Melbourne
				Los Angeles
		Calgary	Toronto	Pittsburgh
		San Jose		Portland
		Sacramento		Dallas
		Los Angeles		
			San Jose	
		New Orleans	San Francisco	San Francisco
		Boston	Philadelphia	Philadelphia
		Cleveland	Boston	Cleveland

Table 5. Notes on LRT Operations in Selected Cities

City	Notes on Operations
Boston, MA	Low and unreliable operating speeds in traffic Lack of priority systems and/or positive control
Buffalo, NY	All at grade crossings protected with traffic signals and LRV preemption - train operator calls signal controller when ready to depart, and the controller preempts the pretimed signal for a green band for LRV travel to the next station
Calgary, Can.	Transit mall - no preemption, fixed signal progression timed to LRT schedule. South & Northeast - total (RR type) preemption. Signal timing developed using TRANSYT-7F
Cleveland, OH	Non-preemption, LRV stop at 4 dangerous crossings
Edmonton, Can.	9 grade crossings in shared ROW - RR gated
Los Angeles, CA	Some at-grade intersections have LRV arrival coinciding with that part of the traffic signal cycle when traffic at the crossing is a minimum, but LRV is delayed at upstream station. System uses custom designed software in the controller which allows full, partial, or total preemption
Melbourne, Aus.	Spatial priority measures - tram lanes & physical separation. Priority at traffic signals - active & passive measures. Sydney Coordinated Adaptive Traffic System (SCATS) provides dynamic active priority phasing. SCATS implemented on a study basis on several routes, then system-wide.
New Orleans, LA	St. Charles - no LRV priority controls, 90 grade crossings, 33 unsignalized. Lee Circle - 22 grade crossings, 2 with special LRT phases
Newark, NJ	One at-grade crossing - LRV stop, warning horn
Philadelphia, PA	Centre City - low speed in mixed traffic, no LRV priority. North Philadelphia - low speed in mixed traffic, no LRV priority
Pittsburgh, PA	South Hills - traffic control for at-grade crossings is RR flashing light signals. One grade separation on South Hills line due to restricted motor vehicle sight distance

Table 5. Notes on LRT Operations in Selected Cities (continued)

City	Notes on Operations
Portland, OR	Downtown Loop - signal progression favoring LRV's; system operates with 1/4 cycle offsets and cycle lengths of 40 to 60 secs; designed non-stop LRV flow at 15-20 mph. First Ave./Gresham - some cab operated full preemption, "decision point" markers on tracks before crossings for LRV in exclusive ROW
Sacramento, CA	Signalized intersections redesigned to accommodate LRV movements, microprocessor signal controllers, some gated crossings
San Diego, CA	Centre City - 4 crossings have stop sign control, 21 have traffic signals - with LRV priority. South Line - 26 crossings are gated w/ flashing lights, LRV has priority except for emergency vehicles East Line - 29 grade crossings protected by gates
San Francisco, CA	Line K - 38 at-grade crossings, 13 controlled by traffic signals, where the LRV has no priority and no special phase. Line L - 45 grade crossings, 2 signalized (no priority), rest controlled by stop signs. Line J - 25 at-grade crossings, 5 signalized (LRV priority at 2). All surface lines have peak 6-10 min. headways
San Jose, CA	Downtown - bus and auto turns restricted. Roadway crossings generally have signal priority. Ten minute peak headways.
Toronto, Can.	96% mixed traffic running. Experimentation with priority systems, which have so far achieved favorable results. Field test of signal preemption on a selected route.

Buffalo, New York. The Buffalo LRT system operates in a center median on Main Street, mostly in a transit mall. The eight roadway grade crossings are all protected with traffic signals and LRV preemption. The operator of the LRV signals the controller when the LRV is ready to depart from the station and either an early green or red truncation occurs. The cross-street traffic at the at-grade crossings are low and therefore the impacts due to preemption are small.

Calgary, Canada. The Calgary LRT system operates its LRT at-grade crossings using two signal phases. This operation is made possible by its extensive use of one-way system trackage. The 73 traffic signals in the defined core area are supervised by a Honeywell master control system (proprietary Urban Transportation Planning System software) and uses a Honeywell Level 6 minicomputer and Honeywell HMP290 fixed time intersection controllers.

The system utilizes three time-of-day plans, which were developed using the TRANSYT-7 simulation model. LRT trains were simulated by treating them as standard vehicles with their special characteristics coded as inputs to TRANSYT. The highest permissible weighting factor was used to ensure that the low number of trains was not ignored in favor of the much higher cross-street volumes. The TRANSYT simulation was relatively successful in providing good signal splits and offsets for buses and trains on 7th Avenue [42].

Detroit, Michigan. The proposed Woodward Corridor LRT line in Detroit is planned to operate in the Woodward Avenue median. At all traffic signals LRVs will have two separate signal phases, one for each direction of travel. These phases will operate as separate phases and will be called only when an LRV is approaching. At the normal cross intersections, the LRV phase, when called, will run concurrently with the parallel through-traffic signal phase. At U-turn pairs ("U-Turn slots" located back to back with an island separating them), preemption will be provided for at least one of the two adjacent slots because there is no space between the slots in which an LRV can stop and wait for a green signal at the second slot. By allowing LRVs to travel only within a single progression band, signal preemption, and its associated disruption, can be limited to one of the two signals at U-turn slot pairs [13].

All side street phases, including U-turn-left-turn phases at U-turn slots, will be subject to "green shortening" to widen or "stretch" the progression window for LRVs in either direction. The maximum amount of window stretching, however, will be set independently for each intersection, for each direction of LRV travel, and for each coordination plan. Traffic signals will be synchronized from an existing regional master controller. All the special control features will be embodied in the individual controllers. Three separate signal coordination plans for use at different times of the day will incorporate all the planned signals in the segment in a single coordination system [13].

Edmonton, Canada. The priority plan implemented by the Edmonton LRT system includes three features. The first was the coordination of traffic signals to minimize the development of vehicular queues across the railway crossing. By controlling the capacity of upstream road signals that feed these links, queue lengths were reduced to acceptable lengths. The second step in the priority plan was to use the periods of time provided by the shadow of the red signals at adjacent intersections for LRT crossings of the road link. The third feature included the use of special features in intersection control, preemption of downstream signals, warning of drivers, and changing of signal sequence in the case of excessive queuing.

Los Angeles, California. The Los Angeles Automated Traffic Surveillance and Control (ATSAC) System provides flexibility in the traffic signal operation, allowing various levels of signal priority to be provided to the Los Angeles light rail system. Preemption is not provided for the LRT in the downtown segments, however, the LRT is able to receive priority at some intersections at certain times of the day.

Partial priority is provided in the form of window stretching which allows the green window provided for the LRT-phase to either start earlier than normal, or finish later than normal. The green time used to widen the LRT phase is taken from other phases, however this extra length of the LRT phase is limited, and no phase with a demand would be skipped in any cycle. Full priority is also provided to the LRT by altering the signal operation to favor the LRT movement in the presence of the LRT. This priority treatment may result in the shortening of some phases and skipping of other phases to accommodate the LRT. The priority level can be controlled by time-of-day, vehicle response or manually [24].

Melbourne, Australia. As a result of a government attempt to improve public transit in Melbourne, Australia, the city introduced tram priority for its 250 km tram network. Priority was provided using the strategic control available through the Sydney Coordinated Traffic System (SCATS). SCATS is a partially adaptive traffic control system which automatically selects signal timing plans based upon traffic conditions and adjusts these timing plans based on traffic conditions at critical intersections. SCATS utilizes selective tram detectors which determines the demand for priority phases. When implementing priority SCATS has the ability to: (1) provide dynamic compensation which helps restore balance to cross-street traffic; (2) provide flexible window stretching; and (3) select priority phases by time-of-day, tidal flow and by intersection congestion.

Portland, Oregon. Along Burnside Street preemption is accomplished by means of inductive loop detectors installed in the track that call for the preempt phase at the traffic signal controllers. Along Holladay Street the ten signalized intersections were designed to work within the pre-existing westbound traffic signal progression which, in turn, was tied to

a north-south progression. Since there was no eastbound progression, eastbound trains could call for a preempt. In the downtown segment, the LRT was inserted into the network using the existing progression band wherever possible [28].

All of the traffic controllers at signalized intersections in the current Portland system are Type 170's with Wapiti Micro Systems software customized for LRT operation. In 1990 two stations were added to the LRT in the downtown area. These stations resulted in the addition of over two minutes to the LRT schedule. To regain this time, the Phillips Vetag system was installed. Prior to the implementation of this system, trains waited at the station and moved within exiting traffic signal progression. This system allowed stationary trains at a station to pre-empt a signal instead of waiting for the progression band [28].

San Diego, California. The original method of preemption provided for the trolley system in San Diego preempted traffic signals to provide a one-way progressive movement for the trolley. This form of preemption did not cause severe impacts to cross-street traffic as the frequency of the trolleys was low. As this frequency increased, from 8 trains per hour in 1981 to 27 trains in 1992, it became almost impossible to accommodate trolleys in both directions. Cross-street traffic and pedestrians also experienced significant increases in delay [63]. Signal preemption was later abandoned for an operating strategy that did not alter the normal operation of the traffic signals, but allowed the trolley to operate efficiently within the existing signal settings. The system works as follows:

1. The trolley dwells in the trolley station until the beginning of the next green light at the first downstream signal;
2. The trolley departs within five seconds of the beginning of the green light;
3. If the departure window is missed, the trolley must wait until the beginning of the next green light;
4. As long as the trolley leaves the station during the departure window, the trolley will receive green lights at all of the signals until it reaches the next station; and
5. The two-phase, fixed-time signal timing favorable to the trolley is always in place and is fitted into the larger network of signals.

San Jose, California. The Guadalupe Corridor LRT in Santa Clara County, California includes a segment in the median north of downtown San Jose. Due to irregular intersection spacing, and several constraints regarding the LRT operation, good two-way progression via signal coordination was not possible. To provide flexibility of operation, a modified National Electrical Manufacturers Association traffic signal controller is to be installed at all intersections. The controller will use standard hardware, but will incorporate

special software. The controller will accommodate eight normal vehicle phases, four normal pedestrian phases, two normal phase overlaps, four special LRT phases, and a time-based coordinator [13].

Time-based coordination is a relatively inexpensive means of allowing traffic signals on the LRT corridor to be synchronized with either adjacent signals on the corridor or signals on the cross street, or both, depending on the cycle length requirements at different times of the day and days of the week. The controller will initiate an LRV phase only if it is demanded and only if both of its associated automobile phases are currently active. The controller has been designed to permit any degree of LRV priority, from none to full, to be implemented at any intersection, for any period of the day of the week, and separately for each direction of LRV travel.

Partial priority is provided by allowing the LRV phase to start earlier than normal or allow the phase to finish later than normal. The controller will allow the signal operator to set limits on the amount of early or extended LRV green in accordance with conditions at each individual signal in each coordination plan. Full priority is a means of inserting an LRV phase in a signal cycle operating in the free or uncoordinated mode. Because the signal is vehicle actuated and not coordinated when full priority is in operation, it will automatically adjust subsequent phase splits to accommodate any unusual queues resulting from the preemption.

Toronto, Canada. Based on a Mainline Traffic Signal Priority Study in 1983, signal pre-emption for streetcars will be installed at 32 signalized intersections in 1992. The study was initiated by the Toronto Transit Commission to investigate the issues associated with providing priority to transit vehicles at signalized intersections. The demonstration project from that study examined the benefits of "non-optimizing priority" signal pre-emption favoring streetcars in mixed traffic. The study was carried out on six signalized intersections on Queen Street, City of Toronto. In a "non-optimizing priority" system, pre-emption is directly responsive only to streetcars along the main arterial route and no consideration is given to changes in vehicle mix, levels of traffic volumes or side street transit [64].

Preemption was provided using an active transponder-loop receiver detection system, with central computer/limited coordination signal control. The central computer maintains the offset of signal cycle times for each signal along the roadway; in this way, progression is maintained. When a streetcar is detected, the mainline green is extended or the side street green is truncated. Under the central computer/limited coordination pre-emption system, streetcar requests for pre-emption would transfer control of the signal from the central computer to the local controller. The local controller could extend the mainline green phase up to 14 seconds.

As a result of the study, travel time savings as high as 20 percent in the PM period and as low as 6 percent in the AM period were experienced by the streetcar. Other vehicular traffic, both on Queen Street and adjacent sidestreets, was not significantly affected by the signal pre-emption.

IMPACT OF LRV ON TRAFFIC SYSTEM

Assessment of the effects of an LRT system on an arterial network and the impacts of different LRT operating scenarios can be determined by the examination of measures of effectiveness (MOEs). Measures of effectiveness quantify the impacts of LRT on other roadway users including other transit vehicles, and can be used to reflect the Level of Service (LOS) of the roadway network. Some MOEs that can be used include delay to automobile occupants, delay to LRT users, "person-delay" at intersections, automobile queue lengths, and the volume to capacity ratio for the intersection. MOEs are also the gauges that indicate the impact of the LRT system on an areawide signal system. When utilized as indicators, these MOEs delineate the LOS of the roadway and its crossings. LOS, however, has been criticized as a criteria in evaluating LRT impacts because it does not consider the volume of people being carried by transit. A principal concern is the need to determine the impact of preferential control of the LRT on the overall system performance. Studies have shown that signal preemption generally results in some loss in intersection capacity. This loss is a function of the LRT frequency and the preemption strategy used.

Delay

A variety of mathematical models and equations have been proposed to quantify the delay to automobiles imposed by LRT. Some of the most commonly referenced equations are presented here, though no effort is made to assess their limitations or range of applicability. A comprehensive discussion of methods of evaluating the impact of LRVs at at-grade light rail crossings can be found in Berry [38].

Stone and Wild [39] :

$$\text{Average individual vehicular delay(sec/veh)} = (0.22)e^{(0.577)(v/c)}$$

where : e = natural logarithm base
 v/c = the volume to capacity ratio of the intersection

Cline, et al [21,22] :

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

where :

- X_{cr} = the crossing volume to capacity ratio
- $X_{cr} = (1/g)(v/s)$
- $g = [C-(CCT+L)]/C$
- $C = \text{LRV headway} = \text{cycle length}$
- $CCT = \text{LRV crossing clearance time}$
- $L = \text{lost time}$
- $g = \text{automobile crossing time}$
- $v/s = \text{demand/saturation ratio}$
- $v/s = (\text{no. of autos/lane/hr})/(\text{saturation no. of autos/lane/hr})$

Highway Capacity Manual (HCM) delay equation, 11-3 [45] :

$$d = 0.38C \frac{(1-g/C)^2}{[1-(g/C)(X)]} + 173X^2[(X-1) + \sqrt{(X-1)^2 + (16X/c)}]$$

where :

- $d = \text{avg. stopped delay per vehicle, sec/veh}$
- $C = \text{cycle length, sec}$
- $g/C = \text{green ratio; ratio of effective green time to } C$
- $X = v/c \text{ ratio for subject lane group}$
- $c = \text{capacity of the through lane group}$

Radwan and Hwang [44] (modified Webster's equation) :

$$d = \frac{9}{10} \left(\left[\frac{C(1-l)^2}{2(1-lX)} \right] + \left[\frac{X^2}{2q(1-X)} \right] \right)$$

where :

- $d = \text{avg. delay per vehicle on the particular approach}$
- $C = \text{cycle time}$
- $l = \text{proportion of the cycle that is green } (g/C)$
- $q = \text{flow}$
- $s = \text{saturation flow}$
- $X = \text{degree of saturation}$

These equations are not an exhaustive list of applicable delay equations and a more comprehensive list of equations is presented in Berry [38].

"Person delay" is presented in Stone and Wild [39] and Cline et al [21,22] as a method of adding a weighting factor for the LRV in due consideration of its passengers. As automobiles are generally considered to have an average ridership of about 1.2 per vehicle, so LRVs have an average ridership. Realistic values for estimated LRV ridership on a proposed system can be based on bus ridership in the same corridor or LRV ridership on an established system in a similar corridor in the same city or another city with similar development patterns. "Person delay" involves computing the delay to all persons using an intersection rather than the number of vehicles using the intersection. Total person delay from a single LRV crossing is computed by multiplying the LRV delay by its ridership and multiplying the average automobile delay by the number of automobiles and the auto ridership. If green splits are established on a "person delay" minimization basis, optimum use of the intersection's capacity would be made on a person-moving basis, but not necessarily on a vehicle-moving basis.

It should be noted that the use of delay has been discouraged by Bates and Lee [1] for the following reasons: (1) no way to account for rail preemption in delay; (2) although over-capacity is definable, over-delay is not; and (3) delay due to auto traffic differs from delay due to rail. They prefer the v/c ratio over average vehicular delay for the definition of level-of-service. The primary impact of full priority on LRT operations is the disruption of the optimal green split.

Queue Length and Dissipation

Another measure of effectiveness for LRT impact quantification is the length of the automobile queue accumulated during the passage of an LRV. Bates and Lee [1] state that while the "LOS identifies the average operating conditions over the peak period, the worst-case queue length indicates the impacts of a specific though-transient condition." The maximum number of vehicles in a queue can be estimated by the formula :

$$Q = q \times r$$

where : Q = queue length, or max. number of vehicles in queue
 q = vehicle arrival rate, veh/sec
 r = maximum red time, sec

The influence of the LRV is felt in the red time that is required for the LRV to cross the roadway. At isolated intersections, the LRV is the only source of red time. In side-of-street and median operations, however, the red time for the LRV is part of the signal timing for the intersection, and it may be difficult to determine the red time (and subsequent added queue length) attributable to the LRV. Factors affecting the red time for the LRV include the amount of advanced warning time before active control device activation, the crossing speed of the LRV, the width of the crossing, the blockage time, the crossing clearance time,

and the lost time. Red time is increased if two LRVs arrive in close proximity to one another in two-way LRV operation. A "worst case" condition exists if an LRV arrives just as an LRV travelling in the opposite direction has cleared the crossing. In addition to its use as a measure of effectiveness in determining the LOS at the crossing, the queue length can be studied in the planning stages to check for interferences with downstream driveways and intersections ("spillback" interference). Dallas Area Rapid Transit (DART) utilizes the above equation with a 1.5 multiplier to account for fluctuations in the vehicle arrival rate. This practice is supported by Gibson et al.[62] and is examined in Berry [38] as an approximation of the 85th percentile queue length. Berry [38] goes on to evaluate the above equation with a 2.0 multiplier in determining an approximation of the 95th percentile queue length. Berry [38] and Gibson [62] discuss more complex methods of calculating queue lengths and contain additional queue length estimation references.

The time required for the queue to dissipate is also a concern when assessing the impacts of an LRV. During periods of high LRV frequency and/or two-way LRT operation, the queue assembled to wait for one LRV may not have sufficient time to disperse before the arrival of a second LRV. This may force vehicles to be delayed twice in the same queue and may cause a secondary queue behind the initial queue. A commonly used equation to determine the queue dissipation time is found in Greenshields et al. [41]:

$$\text{Time (sec) for queue dissipation} = 3.7 + 2.1(n-1)$$

where : n = number of vehicles in the queue

Intersection Level of Service

A simplified methodology for evaluating the level-of-service of streets with at-grade LRT crossings was proposed in Berry [2] using techniques contained in the Highway Capacity Manual. The paper looked at an isolated crossing with no nearby traffic signals. The long cycle lengths and high g/c ratios associated with LRT crossings may border the validity of the equations provided in the HCM. The paper suggests that the analysis of urban and suburban arterials, as presented in Chapter 11 of HCM, can be used for evaluating the impact of an additional traffic delay such as an at-grade LRT crossing.

For signalized intersections, the HCM indicates that capacity and level of service are different entities and that both should be considered. Bates and Lee [1] and HCM Chapter 11 provide equations for the computation of v/c ratio. The Bates and Lee equation is:

$$v/c = \left[\frac{\sum (V - V_p)}{s} \right] \left[\frac{C}{(C-L)} \right] \left[\frac{3600}{(3600-P)} \right]$$

where:	V	= total traffic volume of a critical movement (vph)
	V_p	= traffic volume moving during preemption (vph)
	s	= saturation flow (vph)
	C	= signal cycle length (sec)
	P	= total preemption duration in an hour (sec)
	L	= sum of critical lost time (sec)

Stone and Wild [39] related intersection utilization factor (v/c ratio) to vehicular delay (by their equation previously referenced in this review) and used this relationship in establishing LOS assignments.

Impact on Areawide Signal System

A methodology has been developed by Berry [38] to assess the traffic impacts of LRT based on v/c ratio, average stopped delay, and queue length. This study includes (and ranges beyond) the equations and concerns presented in this review. Analytical tools developed to determine the impacts of LRT on a signal system will, as a matter of course, be a macrocosmic perspective of the issues and procedures presented in this source. Presumably the most efficient means of modelling an arterial network is with pre-existing microcomputer software. Existing, proposed, or hypothetical arterial networks can be created and optimized using programs such as TRANSYT and/or PASSER II. This optimized network and all of its attributes can then be used as the input to a system simulator, such as the Federal Highway Administration's NETSIM, to develop a control case of the network that, based on "runs" of the system, has an associated arterial level of service and quantified measures of effectiveness. The LRT system is then added to the network and the output is compared to the control case. The differences are due to the presence of the LRV, and these differences can be computed for various LRT operating scenarios.

Problems exist, however, in the applicability of the system simulation software to the LRT placement scenario. Though LRV characteristics can be entered as inputs and tracks can be modelled by exclusive roadways or busways, the reliability and compatibility of the LRT placement in the simulator is questionable. Further, the addition of priority schemes for LRT is difficult, if not impossible, within the limitations of the existing and available simulation software.

SUPPORTING MICROCOMPUTER SOFTWARE

Transyt-7F (from TRANSYT-7F User's Manual (Release 6), U.S. Dot FHWA, Oct. 1988.)

TRANSYT-7F is a macroscopic, deterministic simulation and optimization model. TRANSYT-7F is an acronym for TRAFFIC NETWORK STUDY TOOL, Version 7F, where the 'F'

symbolizes that this is the Federal Highway Administration (FHWA) version of TRANSYT-7. The model optimizes coordinated traffic signal systems to reduce delay, stops and, most significantly, fuel consumption. The data required by TRANSYT-7F fall into four general categories: Network data, signal timing parameters, geometric and traffic data, and control data and parameters. There are eight types of outputs provided by TRANSYT-7F including: input data report, traffic performance table, controller timing settings, stopline flow profile plots, time-space diagrams, cycle length evaluation summary, route summary report and special outputs.

One of the two major functions of TRANSYT-7F is to simulate the flow of traffic in a signalized network. TRANSYT-7F is a macroscopic model that considers platoons of vehicles rather than individual vehicles. TRANSYT-7F simulates traffic flow in small time increments. The traffic model further utilizes a platoon dispersion algorithm that simulates the normal dispersion (i.e., the "spreading out") of platoons as they travel downstream. It also considers traffic delay, stops, fuel consumption, travel time and other system measures.

The second major application of TRANSYT-7F is to develop optimized traffic signal timing plans. TRANSYT explicitly optimizes phase lengths and offsets for a given cycle length. To determine the best cycle length, an evaluation of a specified range of cycle lengths may also be made. It should be realized that the absolute optimal solution may not be obtained, but TRANSYT has been demonstrated to give reliable signal timings when used with realistic input data.

TRANSYT-7F is an extremely flexible model and can model a variety of unusual traffic conditions and transportation modes. The network of street and intersections is represented in TRANSYT-7F by a node/link identification scheme. A node is an intersection and a link is a unidirectional traffic movement between two nodes. The standard version of TRANSYT-7F can analyze a network of up to 50 nodes and 250 links (although "larger" versions are available if the user's computer has sufficient memory).

Buses can be explicitly modeled with "bus links" to simulate bus-only lanes. A provision is included to take the dwell time at bus stops into account. Priority treatment can be given to buses by applying high individual weights to the delay and/or stops for the bus links. Dynamic priority treatments, such as bus pre-emption, cannot be modeled in TRANSYT-7F. Some unusual traffic conditions which can be modeled include carpools, mid-block sources, bottlenecks, actuated control, permitted left turns, right turn on red, sign-controlled intersections, shared lane operations, and pedestrians and bicycles.

The signal timing system used by the Calgary LRT system was developed using TRANSYT-7 simulation model. The one-way network allowed most intersections to be two-phased signals. LRT trains were simulated by treating them as standard vehicles with their special characteristics coded as inputs. The highest permissible weighing factor was used

to ensure that the low number of trains was not ignored in favor of the much higher cross-street volume. The transit simulation was successful in providing good signal splits and offsets [42].

NETSIM

The NETSIM network simulation model performs a microscopic simulation of urban traffic flow on an urban street network. It is designed to be applied by the traffic engineer and researcher as an operational tool for the purpose of evaluating alternative network control and traffic management strategies. NETSIM allows the designer to simulate the performance of traffic under a number of alternative control strategies.

The model is based on a microscopic simulation of individual vehicle trajectories as they move through a street network. It has the capacity to treat all major forms of traffic control encountered in the central areas of American cities. It includes a set of "default" values for most input parameters, thereby avoiding the need for detailed calibration in a particular area.

The model is designed primarily to serve as a vehicle for testing relatively complex network control strategies under conditions of heavy traffic flow. It is particularly appropriate to the analysis of dynamically-controlled traffic signal systems based upon real-time surveillance of network traffic movements. It may also be used, however, to address a variety of other simpler problems, including the effectiveness of conventional traffic engineering measures (e.g., parking and turn controls, channelization, one-way street systems, etc.), bus priority systems, and a full range of standard fixed-time and vehicle-actuated signal control strategies.

The street network is defined in terms of a series of interconnected links and nodes. An urban street network is broken down into a set of uni-directional links and nodes. One link would represent a particular direction of travel along a single street between two adjacent intersections. Each link may contain up to five moving lanes. Provision is also made for mid-block "source/sink" nodes representing entrances to parking lots, shopping centers or minor streets not represented on the full network.

Simulation has a number of significant advantages as an analytical device as well as distinct disadvantages. A means of addressing particularly complex analytical problems which may not be susceptible to direct analytical treatment is provided through simulation. The analyst is permitted to focus on specific portions of an overall problem using simulation and experimentation with new ideas which have yet to be put into practice is allowed. Simulation avoids the very real risk of failure implicit in any extensive program of field experimentation and is generally considerably quicker, more flexible and less expensive than other forms of complex, analytical evaluation. A simulation model is still essentially a

simplification of a real-world situation. The results obtained from such a model are only as good as its capacity to reflect a particular real world situation.

NETSIM was [21] used to evaluate the relationship between an intersection crossing volume and the average automobile delay at an isolated crossing. In NETSIM, the light rail transit was modelled as a single lane roadway, and the grade crossing as a two-phase, fully automated intersection. The LRVs arrivals were modelled as buses operating on the track using specified headways. The model, however, gives unconditional priority to the LRT vehicles and makes no allowances for nearby signals and progression [21].

Proprietary Software

Microcomputer software that has the capability to model LRVs in an urban signal system does exist. This software, however, was developed by private corporations to assist them in assessing the impacts of LRT as consultants. The software is proprietary and copyrighted and not available for scholarly evaluation. One such program is ROADTEST, a microscopic simulator described in Fehon et al [26].

CONCLUSION

The findings of the literature review and phone surveys indicate that though a number of models and procedures are available for assessing the service of streets or corridors, few of these models have found their way into (or have been altered for) assessment of LRT operation and simulation. Internationally, simulators exist to model real time interaction of automobiles and light rail vehicles and are incorporated into the control of existing systems; however, these programs would not be easily accessible to parties wishing to evaluate proposed LRT system impacts.

The proposed work plan indicates that all applicable methodologies will be collected, used to simulate operations of existing LRT systems, and compared for their ability to accurately represent conditions in existing networks. Due to the limited number of computerized methodologies that are flexible enough to analyze LRT system impacts, several tasks from the original work plan have been combined. Essentially, Task 3 (Collect and Evaluate Theoretical Methodologies Used by Other Agencies) and Task 5 (Test Selected Theoretical Methodologies Against Operational Data) have been accomplished simultaneously, based on the information found in conducting the literature review and the recommendations of the technical committee. The article sources and the members of the technical committee have pointed to the FHWA's NETSIM as the package that is flexible enough to simulate and analyze the effects of LRT operation in an urban signalized network. The software is readily available to the interested agencies and it has been used and proven for years as a means of evaluating myriad traffic operating scenarios. Since NETSIM can only simulate traffic conditions, TRANSYT and/or PASSER will be used to develop signal timings for proposed or optimized networks. Each of these programs has also been used to evaluate existing and proposed traffic scenarios for years and is a reliable and accurate tool.

Given that NETSIM has been selected as the best choice for simulating and assessing the impacts of LRT on a signalized network, the next phases of the project will continue as ordered in the work plan. Existing facilities will be observed and data collected to input into NETSIM and/or TRANSYT. These programs will then perform theoretical simulations of the observed traffic in the study cities. The results of the comparison of observed and modeled facilities will be used to calibrate and fine-tune the simulation of traffic operations in the network. Finally, a reference guide will be assembled to guide interested parties in using NETSIM and/or TRANSYT to model proposed alternative for LRT operation.

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APPENDIX A

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APPENDIX B

RESEARCH PROJECT 12782
Technical Committee Meeting 1

- I. The meeting took place at 9:00 am on April 27, 1992 at the TTI office in Arlington, Texas.

Meeting attendees included:

Rick Berry; DeShazo, Starek & Tang
Janice Daniel; TTI
Dan Fambro; TTI
Doug Hunt; University of Calgary
K.R. Marshall; Barton-Aschman
Chris Poe; TTI
Carol Walters; TTI
Robert Wunderlich; Barton-Aschman

- II. Light Rail Transit Environments

A. Crossing Types

1. Mall Situations
2. Isolated Crossings
3. Median Running
4. Networks
5. Adjacent Side Running

Dependent on type of crossing, different degrees of preemption might be selected. Thus, analysis tool must provide ways to handle a variety of situations.

B. Methods By Which Trains Run

1. Trains may run with the signals; Looked at as simply another vehicle.
2. Train preempts the signal cycle; No consideration is given to the signals.
3. Adaptive System where train and signal system communicate and adapt to one another.

Los Angeles tried adaptive system; yet, this has been scrapped and LRT now runs more like a trolley.

- II. B. Dallas has proposed a rearranged signal system for light rail, which is really the same as adaption/preemption.

North Carolina has a working adaptive system. Trains run in the greenband; Signals are adapted to fit the trains--they are not on fixed-times.

Melbourne has a working sophisticated adaptive system.

III. Implementation

The degree of system implementation is directly related to the degree of cooperation between transit and signal authorities.

In Toronto, Calgary, and Melbourne, one entity has control over both transit and signals.

IV. Establishing A Tool

Ultimately, strive to develop one system that addresses transit and street/traffic concerns.

There is a need for one tool that helps find the optimum for both transit and traffic.

Desire is to design a tool which shows what works best for all travelers-- not one or the other.

Must establish limits on use of tool; Is it to be used for planning purposes or for operational purposes?

V. The Models

- A. V/C Ratio: Used to estimate volume to capacity at the crossing and to determine saturation flow; Compare V/C ratio with rail and without rail; This is one of the most basic models and is used in isolated crossing environments.

- B. Transference: Look at adjacent signalized intersections and their red times at cross streets and compare this to the light rail intersection. Use LOS findings from like intersection to predict what will occur at light rail intersection.

- C. Options Analysis

- D. Time-Space Diagram

V. E. Network-Based Tools

1. TRANSYT

In Calgary, used mall applications to develop fixed-timing plans. No preemption or priority is given to transit once the green-band is established within the fixed-timing plan.

2. TRANSYT-7F

This has been used in median-running situations with completely fixed times (trains conform to signals). One of the limitations of the program is that it has to run in conformance on a fixed-time basis. TRANSYT 7F is not used as an optimization tool. It is more of an evaluation tool. It may be used in conjunction with such programs as PASSER.

3. NETSIM

Provides a visual output (gives credibility to presentations); Trains are run as buses and crossings as signalized intersections in this program; NETSIM does not allow for random train arrivals. Signals are run as either fixed-time or actuated signals. It is not capable of evaluating a preemptive situation right out of the box; yet, you can fake it and simulate preemption. NETSIM will not optimize the system, either, so it is generally used in conjunction with another program/method. NETSIM appears to have a great deal of promise, however, for light rail applications as it could be modified and adapted to include light rail parameters.

4. PASSER III (used in median running situations)

5. SINTRAL

Used primarily in Canada; Used in isolated intersection situations; It is a tool for doing delay and probability of clearance calculations using queuing theory, takes into account all of the turning movements given the input volumes. HCM software is used in similar situations in the United States.

V. E. 6. CONTRAM

Used in Calgary; Developed by TRNL in England; CONTRAM has variable O/D matrix capabilities; It is a traffic assignment model but it can vary conditions at intersections in response to the volumes it predicts. Therefore, it actually does some design work and then iterates back and does its traffic assignments; It can provide delays at intersections, queue lengths, and a lot of other design criteria; Very data-intensive.

7. SATURN

Uses same traffic model as TRANSYT; SATURN allows for variable demand and can have three levels of intersection simulation. Serves as the "half-way house" between TRANSYT and a full regional planning four-step model; Seems very likely that this program has been used with light rail transit issues.

8. E-SIM

This is a train performance model. It provides operation simulation of light rail--tells when the train is or isn't breaking, how much electricity it is using, its speed, etc. E-SIM does allow the user to input things from a signal system (i.e. signal timing, stopping points). It is train-oriented, yet allows for some input of effects of signalization, stops, etc. on train performance.

9. SCOOT

Used in Alberta (has had its problems); Uses same traffic model as TRANSYT; SCOOT is supposed to be a traffic adaptive package. It has the capability of detecting queue lengths at upstream intersections and changing traffic patterns at downstream intersections by making signal timing adaptations; It is supposed to adjust the network; In reality, it seems to never really catch up.

10. Traffic Assignment Models

- a. M-TAP: Has a rail section
- b. COR-FLOW: not applicable to this project
- c. FREE-FLOW: not applicable to this project

- V. E. Currently, none of the programs tell you anything about what happens to the train; all basically tell you about the traffic.

With programs, the decision making is still left up to the analyst running the program. The software is only designed to be a tool. So far, nothing in the programs searches for an optimum case.

VI. Accident Data

How are safety issues going to be appropriately incorporated into this project? How much is germane to this project since the stated scope of the project is to address traffic impacts?

Should at least mention that safety is an issue with a statement saying that this subject is beyond the scope of the current project (possible subject for future research).

Useable accident data is not easily obtainable; Transit entities generally keep accident data while cities/counties keep traffic volume data. The two must be merged to be able to make predictions or to establish useable accident rates.

Transit agencies are mitigation-oriented with respect to accident data. They want to know where accidents are occurring and what is causing them. They are not as interested in accident rates.

RESEARCH PROJECT 12782
Technical Committee Meeting 2

- I. The meeting took place at 9:00 am on May 29, 1992 at the TTI office in Arlington, Texas.

Meeting attendees included:

Ed Collins; TxDOT, D-11
Owen Curtis; JHK & Associates
Dan Fambro; TTI
Jim Hanks; JRH Transportation Engineers
John Kelly; TxDOT, Dallas
K.R. Marshall; Barton-Aschman
Chris Poe; TTI
Carol Walters; TTI
Robert Wunderlich; Barton-Aschman

- II. Examples of Existing and Proposed Light Rail Transit Crossings

- A. In California, light rail vehicles at isolated crossings have not proven to be detrimental to side street traffic, even when side street traffic is heavy, because the amount of time taken from the side streets during a given signal cycle for train preemption is not significant.
- B. In San Diego, CA, a separate right-of-way light rail line has been proposed. This line would involve 40 random gate closures per hour with a minimum closure time of 40 seconds per closure. The line is to be located near a freight right-of-way with commuter rail which further complicates the traffic situation. Grade separation for this line has been received negatively by the public due to aesthetic reasons. All of these factors have made this rail line a difficult one to analyze.
- C. In San Jose, CA, a median running light rail crossing operates with variable preemption. The controller allows for variable preemption by the train except during designated times when the side streets preempt the trains. If the train does have to wait, it is normally for no more than 20 seconds at any one time.
- D. In Portland, the operator can vary the speed of the train to coincide with traffic signals, when necessary. Portland uses V-tag.

- II. E. In Los Angeles, they have the capabilities and design to use total preemption with their light rail lines; Yet, due to political pressure, they choose not to use it and have a poor transit signal system.
- F. In Dallas, train operators will not get to know when preemption is coming; Thus, they will not be able to vary speeds to coincide with the traffic signals, when necessary.

Train arrivals are never completely random. There is some predictability to them--they are random only within a given signal cycle. The term "Not Synchronized" may be more correct than "Random."

Side-running trains without gates are a real problem because right-turning vehicles often ignore signs/lights and turn into trains.

III. Methods of Evaluation

Transit models look at ridership; Traffic models look at delay and speeds. What is needed is a relationship between the speed of a transit vehicle and the level-of-service.

Presently, we are able to do things with software-driven controllers that we cannot evaluate. There is a gap between reality and our ability to simulate/model. This study can help close that gap.

Signal operation within the CBD is controlled by pedestrians. While there is no way to model pedestrian activity in useful manner, what is being done in CBD's is working.

Need to work towards interaction between train performance models and signal timing models. The evaluation model needs to have the ability to model the train, in some respects (i.e. be able to input certain headways, dwelling times, to simulate some train arrival times and some train performance characteristics).

Initial timing plans are usually generated by PASSER or TRANSYT 7F for evaluation purposes. NETSIM will not generate timing plans.

NETSIM is only an evaluation tool. It is not an optimization tool and does not provide a "Big Picture" view of a situation. Presently, train crossings are input as signals which occur at a set time. A coordinated signal system with random train arrivals cannot be run on NETSIM at this time.

- III. T-Model is an intersection capacity model that can be run with or without a train to see how a given intersection operates. The runs can be compared with differences and worst-case scenarios noted.

Need a tool to help decide how to run the train, either as a train with preemption or as a vehicle in traffic; May also need another tool to assist in planning and to help in deciding how to operate the LRT; Still, another separate tool may be needed to help determine whether grade separation is needed.

- IV. Developing the Evaluation Tool

The evaluation tool should handle operations, not merely planning. The tool should provide pieces of information which are critical to making the decision of grade-separation. The tool will not make the decision on its own, rather it will help the engineer make a rational choice.

Due to time and budget limitations of this project, it does not appear possible to develop one single tool that will both optimize the signal settings and be able to do evaluations on a microscopic basis. It might be better to look into modifying existing evaluation programs.

Currently, all modeling programs are moving towards being able to exchange data and talk back and forth from one program to another (i.e. One might develop a timing plan in PASSER that is written to an output file that TRANSYT can then read and optimize. Then, this might be written to another output file that NETSIM could read and further evaluate problem locations).

There is not a single tool that can look at and evaluate all of the different LRT alternatives presented in the previous meeting. FHWA is committed to the use of NETSIM in its evaluation process now and in the future. Do we follow them or create another path?

- V. The Ideal Evaluation Tool

The ideal evaluation tool would:

- A. Simulate the state-of-the-practice in terms of signal control (No present model does this, at least in the US).

Presently, TRANSYT 7F simulates/optimizes a fixed-time grid. It has no traffic responsiveness in it with no ability to put in preemption. This is how most of the models work.

- V. A. Simulation is very far behind the state-of-the-practice.
- B. Have some capability to model train behavior, both in terms of individual train characteristics as well as operational characteristics of the system itself.
- C. Actually simulate gates, as opposed to being represented by a traffic signal.
- D. Be calibrated into real-world conditions.

The input should at least give you ramifications of it--"Yes, you did get service," or "No, you did not get service."

The tool should not only be capable of simulating such things as signal controllers, phase and cycle changes, speeds, and train arrival times, it should also be capable of being compared to what happens in the real world.

- V. E. Give outputs that are not merely averages and calculated delays.

The tool should at least tell us what the implications of delay are; Might consider looking at elapsed person time between two points (instead of delay as the term carries a negative connotation) and then compare the times without rail, with rail and no grade-separation, and with grade-separated rail.

VI. Measures of Effectiveness

A. Delay

If one only considers delay, the best light-rail system would always be grade-separated (because there would always be less delay). Yet, this is not always feasible, financially or geometrically.

When looking at delay, trains carry more weight because they carry more people, thus justifying delay to others. Delay needs to be in relative time.

With present programs, the "delay" we get is an average per vehicle (meaning that it spreads the delay out over the vehicles that are delayed and those that are not). It would be interesting to see what the delay is on only those vehicles which are actually delayed. The average delay often makes the delay appear to be no big deal; however, those who are stopped by the train do experience a certain level of discomfort.

- VI. A. There is more to delay than just delay at the crossing. But, how far do you go beyond the crossing in an evaluation? This must be decided case by case and often depends on the size of the system. Generally, try to go out far enough to reach a point where there is zero impact on the extremities.

People may have to sit at a crossing when there is no train on a fixed system. This leads to frustration, increases public mistrust and dissatisfaction with transit entity.

- B. Queuing

Catastrophic Queuing is queuing that is not seen as acceptable (when traffic backs up onto freeway ramps, through gates, or onto tracks). It is possible to design a system which avoids these catastrophic incidents, which is safe; however, this is often at the expense of efficient operation. A methodology needs to be designed to help determine places where it is impossible to avoid catastrophic queuing and whether grade-separation is the only viable alternative.

**RESEARCH PROJECT 12782
Technical Committee Meeting 3**

- I. The meeting took place at 9:00 am on July 21, 1992 at the TTI office in Arlington, Texas.

Meeting attendees included:

Rick Berry; DeShazo, Starek & Tang
Janice Daniel; TTI
Curtis Herrick; TxDOT, D-18
Greg Krueger; TTI
K.R. Marshall; Barton-Aschman
Ken Ogden; Monash University, Australia
Chris Poe; TTI
Carol Walters; TTI
Poonam Wiles; TTI
Jim Williams; University of Texas, Arlington

- II. Ken Ogden gave a slide presentation of LRT in Melbourne, Australia.
- A. Melbourne, Australia has a population of 3.1 million. The transit system includes:

Heavy rail	17 routes	208 miles	172 train sets (6 cars each)
LRT	42 routes	206 miles	630 vehicles
Buses	207 routes	290 miles	1200 vehicles

The urban area is low density with single family homes and auto ownership is high. No extensive freeway system exists, and vehicles use the arterial street system.

- B. LRT System

LRT stops are spaced in hundreds of yards in the CBD and at 1/4 miles in the central city region. LRT speeds in pedestrian malls are 5 mph. LRT operates in exclusive, semi-exclusive, and shared right of way. Crossings are primarily at-grade, and the LRVs operate in medians, on the side of streets, and in mixed traffic lanes.

II. C. Traffic Control

The Sydney Coordinated Adaptive Traffic Control System (SCATS) is used in Melbourne. SCATS is a hierarchical system that uses a central computer for monitoring and regional computers for operating the local intersection controllers.

SCATS incorporated the LRT system to provide priority to LRVs by providing priority in peak periods so that the LRV can clear the intersection on the 1st available green and priority in the counter peak direction so that the LRVs can get back.

LRV priority accomplished by:

1. Phase extension (hold green until vehicle clears);
2. Early start;
3. In shared lanes, gives green to lane with LRV to clear autos ahead of the LRV;
4. Special LRV phases; and,
5. Non-LRV phases suppressed in order to serve light rail.

SCATS has real-time vehicle actuation and can detect priority calls. If the LRV arrives during the green, no priority is given. Detectors are placed up to 600 feet ahead of the intersection, and they are located at the stop line to hold priority phases. A full fault monitoring system ensures reliability.

A predictive model called SCATSIM is used along with SCATS to enable the software to be used as an evaluation tool.

**RESEARCH PROJECT 12782
Steering Committee Meeting 1**

- I. The meeting took place at 9:00 am on August 19, 1992 at the TxDOT Training Center in Austin, Texas.

Meeting attendees included:

Ed Collins; TxDOT, D-11
Jim Cotton; TxDOT, D-11
Mildred Cox; City of Dallas
Dan Fambro; TTI
Don Garrison; TxDOT, Houston
Dave Gerard; City of Austin
John Kelly; TxDOT, Dallas
Ernie Martinez; METRO, Austin
John Sedlack; METRO, Houston
Steven Venglar; TTI
Carol Walters; TTI

II. Project and Report

- A. Monterrey, Mexico, a sister city with Dallas, is a possible study site (existing LRT system) because it has similar problems as Dallas.
- B. Role of steering committee in this discussion is to tell researchers the needs that you will be faced with (i.e. tool addresses all configurations)
- C. Identify the different types of situations LRT may run through: grid, downtown, etc. In reports, may want to raise cost effectiveness issues and indicate how to come up with future turning movement counts (planning horizon suggestions). Also, reports may mention involved decision process, planning horizons, modeling, transit selection options.
- D. Queuing and capacity analysis involved in study. If possible, include concerns such as reliability and effects of operating speeds on operations and ridership.
- E. Not dropping one level of service or below LOS E could be threshold for decision making when analyzing shared ROW operations.

III. Issues from Represented Cities (Houston, Austin, Dallas)

- A. Houston looking at commuter rail (similar characteristics in crossing types), but vehicles have longer headways, are more difficult to stop, and run at higher speeds. Inputs for vehicle characteristics should be possible to make tool flexible. In future, if capacities warrant, commuter rail lines may convert to light rail. Long Beach line in LA has freight, light rail, and commuter rail in same corridor.
- B. The city of Austin is working with LRT ideas with a year 2000 planning horizon. The system would operate with 15 minute headways, have single and double track, run in the median in shared ROW. Barton Aschman doing traffic impact analysis (TIA). Metro has draft Environmental Impact Statement. System will have no grade separations and it will run with the flow of traffic.
- C. Austin is probably going to prohibit left turns at driveways and unsignalized intersections where LRT would run.

