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16. Abstract

As the engineering and planning communities continue their progress toward managed and integrated transportation systems, transit will play an increasing role. Fifteen United States cities have already selected and implemented light rail transit (LRT) as a rail transit alternative. As engineers plan and design new or expanded systems, it is essential that they have at their disposal the techniques and procedures necessary to make decisions for LRT placement, system design, and operations.

This report, the fourth and final report for project 0-1278, combines and enhances the information contained in the three interim reports and contains a step-by-step procedure for analyzing LRT at grade crossings and crossing impacts within signalized networks. Based on the proposed system features and location, transportation analysts identify crossing type and environment. They then select a model based on listed criteria, code and calibrate the model to existing conditions or values provided, and perform the analyses. The procedure includes checks for system failures. Finally, analysts assign user costs to the LRT impacts identified and quantified by the procedure, and select the optimum alternatives for LRT operation.

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DEVELOPMENT OF ANALYTICAL TOOLS FOR EVALUATING OPERATIONS OF LIGHT RAIL AT GRADE WITHIN AN URBAN SIGNAL SYSTEM

FINAL REPORT

by

Steven P. Venglar
Assistant Research Scientist

Daniel B. Fambro, P.E.
Associate Research Engineer

and

Carol H. Walters, P.E.
Research Engineer

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

IMPLEMENTATION STATEMENT

The following report is the final report for Study 0-1278, *Development of Analytical Tools for Evaluating Operations of Light Rail At Grade Within an Urban Signal System.* The completed research provides engineers with a methodology and step-by-step procedure for assessing the impacts of an LRT system on signalized urban arterial street intersections and networks. By analyzing various configurations of roadway and trackage geometrics and signalization alternatives, engineers can make informed decisions about 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. The engineers in charge of the project were Carol H. Walters, P.E. # 51154, and Daniel B. Fambro, P.E. #47535.

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J. Douglas Hunt	University of Calgary, Canada
Kenneth R. Marshall	Barton-Aschman, Associates, Inc.
Kenneth W. Ogden	Monash University, Australia
Robert N. Wunderlich	Barton-Aschman, Associates, Inc.

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SUMMARY

As the engineering and planning communities continue their progress toward managed and integrated transportation systems, transit will play an increasing role. Fifteen United States cities have already selected and implemented light rail transit (LRT) as a rail transit alternative. As engineers plan and design new or expanded systems, it is essential that they have at their disposal the techniques and procedures necessary to make decisions for LRT placement, system design, and operations.

In their effort to develop an LRT analysis procedure that was comprehensive enough to analyze a vast variety of LRT at grade crossings and sufficiently detailed to guide analysts through the necessary analysis steps, researchers combined experience from surveys of cities with existing LRT systems, a literature review, modeling studies, and traffic software studies to produce an eight step LRT at grade crossing analysis procedure. While the three interim reports for this project document the surveys, reviews, and studies conducted as part of the research, this report, the fourth and final report for project 0-1278, contains the final step-by-step procedure.

In the initial steps of the procedure, the analyst determines the LRT crossing type and environment. The procedure allows for the analysis of both existing systems and alternative alignments for proposed systems. Once identified, the system features and location determine the appropriate software for the at grade crossing analysis. If the LRT system is an existing system, analysts assemble data on the traffic volumes, geometry, and signal settings found at the at grade crossing or network. If the system is a proposed system, the analyst must use projected volumes, proposed geometric features, and signal setting estimates as input. Calibration is the next procedural step. Through data collected in the field or values recommended in this report, the analyst adjusts the model to replicate traffic behavior observed or expected in the field. When the calibration adjustments are complete, the analyst performs the final simulation of the control and placement alternative/alternatives. Finally, after checking for system failures, the analyst assigns user costs to the LRT impacts identified and quantified by the procedure and selects the optimum alternatives for LRT operation.

1.0 INTRODUCTION

1.1 BACKGROUND

Congestion in freeway and arterial street networks is an increasing problem in urban areas throughout the country. In an effort to abate the excess fuel consumption, automobile emissions, and delays to road users brought about by congestion, cities are pursuing rail transit alternatives. In Texas, for instance, Houston has examined and is presently developing commuter rail, and Dallas is presently constructing the Dallas Area Rapid Transit light rail transit line. Among the rail transit alternatives of commuter rail, heavy rail, and light rail, light rail is the cheapest and most flexible due to its ability to operate at grade and even in mixed operations with street traffic.

When in the process of planning a future light rail transit (LRT) system, or even for examining operational alternatives for an existing LRT system, it is essential that tools are available to assess the impacts of transit on the existing transportation system. Measures of effectiveness (MOEs) describe these effects, which include delay to motorists and transit riders, fuel consumption, emissions, and overall mobility. With such information, it is possible to select the best alternatives for implementation of LRT. Models simulate the LRT system operations and produce the necessary database of MOEs. The models can range from mathematical procedures to computer simulation. To efficiently process the necessary information and maintain records of the myriad variables describing the interaction between drivers, vehicles, and the roadway, researchers and practitioners have developed a number of computerized techniques.

1.2 PROBLEM STATEMENT

As LRT becomes an increasingly popular transit alternative, there arises a need 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. Past research led to the developement of analytical tools to optimize and 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.

Following the development of a method for computing LRT impacts, any shortcomings in the procedure can lead to a failure of the planned system. Therefore, it is essential that the model produce accurate and reliable results. Model calibration helps ensure that the model outputs accurately represent the effects of the planned LRT system. For this report, calibration consists of adjusting model inputs and default parameters to model the true data from field observation as accurately as possible. A primary output from the analysis techniques and models should be an output or combination of outputs that identify whether or not the proposed LRT system will work or might have problems. Excessive delays or queues that spill over into upstream intersections are examples of system failure, and the analysis should identify these problems and methods for differentiating problems due to LRT implementation from those already present in the traffic network.

1.3 PURPOSE

The purpose of this report is to provide transportation analysts with a procedure for determining and analyzing the impacts of at grade LRT operations on intersections within arterial street networks. Microcomputer transportation modeling and analysis software is emphasized to expedite the analytical process and generate measures of effectiveness that describe the networks both before and after the conceptualized LRT system is located within the modeled network. The procedure contains checks to monitor for system failures and outlines methods of interpreting the output from the software and translating the output to system user costs.

1.4 SCOPE

This report contains a recommended procedure for using publicly available microcomputer traffic analysis programs, privately developed traffic analysis programs available for purchase identified through contacts made during the course of this investigation, or a combination of these programs to determine the impacts of at grade LRT on intersections and networks. A degree of user familiarity with the programs is assumed. The procedures highlight details that should be considered when coding the programs or recommendations for analyzing particular sets of conditions. This document does not attempt to serve as a user's guide for the recommended models; however, the combination of the original software user's guide and the information contained in this report should prove adequate for LRT analysis.

1.5 ORGANIZATION

This report has been organized into four sections. Introductory material and project objectives have been provided in Section One. Section Two contains an overview of the role the analytical procedure outlined in this report plays in the evaluation of LRT at grade crossings. As microcomputer analysis models play an important role in the procedure, Section Two also describes the general nature and some features of the programs recommended for use in LRT analysis. Section Three outlines and presents the procedure itself. An analysis flowchart is linked with Section Three subheadings and provides the framework for evaluating LRT at grade impacts. Users are taken through each step, and ultimately select and use a model to provide MOEs for the at grade LRT scenario/scenarios under consideration. Research conclusions and recommendations are contained in Section Four. Appendices contain examples of data collection sheets applicable to the data collection phase of LRT analyses and descriptions of other models, developed internationally, that have been designed for LRT analysis .

2.0 BACKGROUND AND MODELING SOFTWARE

The initial steps of the work plan were devoted to creating project advisory and technical committees, assembling the committees for group meetings and discussions, and reviewing the literature for methods of analyzing LRT crossings. The first interim report for this project (*1*) includes the results of these meetings, the literature review, and some summary statistics from cities currently operating LRT systems.

Further investigation into analytical tools for generating MOEs for traffic and LRT systems resulted in the background material for the second interim project report (*2*). Two microcomputer programs, the Federal Highway Administration's TRAF-NETSIM and JRH Transportation Engineering's TransSim II^{TM}, were selected for detailed analysis, calibration, and validation. Simulation results from both models were compared with field data and procedures were developed to calibrate the models to known field conditions. Researchers tested and verified the ability of the programs to accurately model LRT systems currently operating in Los Angeles and Long Beach, California, and Portland, Oregon.

A third interim report (*3*) summarized the means and methods of analysis of the impacts of at grade LRT on traffic operations, especially within traffic signal system environments. The primary means and methods identified are those that the general traffic engineering practitioner can apply without a specific background in advanced computer simulation. The results of these procedures vary depending on the level of analysis, from general order of magnitude results to finely detailed estimates of impacts. A number of questions and concerns are raised about types and quantification of impacts, how impacts are attributed to transit, and issues to be addressed in LRT system design.

This final report was made possible by the experience and research results obtained from the previous reports. It is not, however, a compilation of all findings of the previous reports, and analysts should review all three reports before performing the analysis procedure in this report. The recommended analysis methodology is intended to assist the user in applying the most appropriate microcomputer tool to the LRT analysis scenario at hand. Once this tool is selected, the analyst can follow the procedural steps to generate the performance measures required for determining the impacts of the at grade LRT crossings on the network.

2.1 ASSESSING IMPACTS OF LRT ON TRAFFIC SYSTEM

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 MOEs. MOEs 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 include delay to automobile occupants, delay to LRT users, "person-delay" at intersections, the volume-to-capacity ratio for the intersection, queue lengths, number of stops, and the travel times on adjacent streets. 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 priority generally results in some loss in intersection capacity. This loss is a function of the LRT frequency and the priority strategy used.

Another MOE for LRT impact quantification is the length of the automobile queue accumulated during the passage of an LRV. Bates and Lee (*4*) 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." During periods when demand exceeds capacity, queue lengths can build through several cycles and may even spill back into upstream intersections.

Presumably the most efficient means of modeling an arterial network is with pre-existing microcomputer software. Existing, proposed, or hypothetical arterial networks can be created and optimized using programs such as EVIPAS, PASSER II, PASSER IV, and/or TRANSYT. This optimized network and all of its attributes can then be used as the input to a system simulator or evaluation tool, such as the Highway Capacity Software (HCS), NETSIM, TEXAS, and/or TransSim II^{TM}, to develop a control case of the network that, based on "runs" of the system, has an associated arterial level of service and quantified MOEs. 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 are computed for various LRT operating scenarios. This analysis is also important in that problems in the modeling stage, such as locations where high delays occur or where queue length exceeds available storage space, indicate potential failures of the system. It is important to differentiate between MOE impacts, such as delays and queue lengths, that occur based on the network structure before LRT and those which are directly attributable to the presence of LRT.

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 modeled 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. To compound the problem, there has been little agreement to date on how LRT analyses should be performed. Identifying the range of applicability of each of the previously mentioned programs and the role that each can play in LRT at grade analysis is essential to achieving the purpose of this report. The following paragraphs provide descriptions of the selected software packages.

2.2 HCS

Courage and Wallace at the University of Florida developed the current HCS software for the Federal Highway Administration. The program calculates saturation flow rates, average stopped delay, average travel speed, level of service, and other MOEs based on the *Highway Capacity Manual* (HCM) (*5*) methodologies, the widely accepted standard for analysis of signalized intersections, open networks, and arterial networks. The program is straightforward and easy to use; however, it can only be used for one intersection or direction on the arterial at a time. For further information, consult the *Highway Capacity Software User's Manual* (*6*).

The geometric and traffic input data for each intersection analyzed in the HCS include the number of lanes per movement, the movement traffic volume, lane width, grade, percent, parking, pedestrian, and arrival type. Signal inputs into HCS include phase selection, sequence, green duration, yellow plus red clearance time, lost time, and actuated/pretimed operation.

The output of the HCS is broken down under the headings of capacity and level of service. Capacity outputs include volume-to-saturation flow ratio (v/s) and volume-to-capacity ratio (v/c). Level of service outputs include green-to-cycle-length ratio (g/C), the lane group delay and level of service, and the approach delay and level of service.

2.3 PASSER II

The Texas Transportation Institute at Texas A&M University developed the **P**rogression **A**nalysis and **S**ignal **S**ystem **E**valuation **R**outine for the Texas Department of Transportation. The program analyzes and optimizes isolated intersections, arterial streets, and open arterial street networks. Features include provisions for actuated and pretimed control, an assistant function key for calculating saturation flow rates using HCM methods, and the capability of modeling permitted left turns. For evaluation purposes, PASSER II estimates the MOEs for movements corresponding to NEMA phases at individual intersections as well as overall MOEs for the entire arterial network. The MOEs used by the program include v/c ratios, delay, queues, stops, and fuel consumption. Additionally, PASSER II evaluates the progression bandwidth efficiency and attainability for the existing or optimum signal timing conditions. For further information on the program, refer to *Arterial Signal Timing Optimization Using PASSER II-90* (*7*).

The input requirements for PASSER II vary depending on whether an isolated intersection is being analyzed or whether a progression analysis for an arterial is being performed. For an isolated intersection analysis, the input data requirements include basic traffic and intersection data, signal phasing, vehicle turning movements, and saturation flow rates. Performing a progression analysis for an arterial requires intersection spacing, progression speeds, allowable cycle lengths, and minimum green splits for each movement.

PASSER II produces three levels of MOEs depending upon the evaluation alternative performed. An isolated intersection analysis produces the following MOEs: saturation ratio, delay, average stops, and average fuel consumption for each movement. This evaluation also provides MOEs on the overall intersection operation such as the average intersection delay, average fuel consumption and the minimum delay cycle length.

The output report for an arterial progression analysis is produced in six parts. The first part contains a simplified restatement or echo printout report of the input data, one page per intersection. The second part includes all error messages. The third section includes a summary of the optimized solution parameters for the arterial progression or the evaluation of the signal timing settings. The fourth section contains signal-timing and phase evaluations for each intersection and all phase movements. The fifth part of the output is a combination of all the signal-timing plans along the arterial provided in one table for easy reference. Offsets of all intersections in this table are synchronized with respect to the master or reference intersection. The sixth and last part of the PASSER II-90 output is the optional time-space diagram.

2.4 TEXAS

The Center for Transportation Research at the University of Texas developed the TEXAS model. The TEXAS model evaluates and simulates existing or proposed conditions. A graphics display illustrates the speed, location, and time relationship for every simulated vehicle. This program simulates pretimed, semi-actuated, and fully actuated control, and evaluates emissions of air pollutants at the intersection. The TEXAS model is primarily used for evaluation, not optimization.

Data required by the TEXAS model is entered through two separate programs. The first program allows the user to enter data describing the geometry, drivers, and vehicles in the modeled intersection. The second program allows data entry for information required by the simulation processor of the TEXAS model.

Output from the TEXAS model includes the instantaneous speed, location, and time relationship for every simulated vehicle. Data manipulation allows for display graphically on the computer screen or in a written tabular format that provides summary statistics about traffic and traffic signal controller performance. For further information on the TEXAS model, refer to *Texas Model Version 3.0* (*8*).

2.5 EVIPAS

The University of Pittsburgh developed **E**nhanced **V**alue **I**teration **P**rocess **A**ctuated **S**ignals, an optimization and simulation model for isolated intersections under actuated control, for the Pennsylvania Department of Transportation. EVIPAS can analyze and develop almost any phasing pattern available in a standard NEMA or Type 170 controller. A variety of MOEs can be used to determine optimal signal settings for pretimed, semi-actuated, fully actuated, or volume-density control with or without pedestrian actuations.

Two separate files contain the inputs required by EVIPAS. The analyst enters the data using a data entry program known as EzVIPAS. The first file, which is the location of geometric and other fixed data elements, contains run identification and default overrides, approach information, lane and detector information, signal system setup, signal phasing definition, traffic volume, and pedestrian flow. The second file consists of run control information, cost and emissions parameters, signal timing start values, optimization flags, and lower and upper bounds for optimized parameters.

EVIPAS produces four groups of output. The first three summarize the input data and the model's optimization progress. The primary output file contains the intersection performance output, and within this file is the delay, signal performance, signal settings, and final cost information generated by the model. EVIPAS generates a variety of delay measures, average phase and cycle length, and average and total cost. Additional information on EVIPAS is available from the *EzVIPAS 1.0 User Guide* (*9*).

2.6 PASSER IV

The Progressive Analysis and Signal System Evaluation Routine, Model (PASSER) IV is an advanced network signal timing optimization model. The Texas Transportation Institute at Texas A&M University developed the program for the Texas Department of Transportation. This program is the only practical computer program that optimizes signal timings for large multi-arterial networks based on maximizing platoon progression. PASSER IV maximizes progression bandwidth on all arterials (one-way and two-way) in closed networks and explicitly handles one-way streets. The program complements PASSER II and TRANSYT-7F. In the present version of PASSER IV, it is possible to specify the splits and phasing sequences. Offsets, however, can not be specified. Hence, one cannot simulate the existing conditions. It is expected that in the future versions of PASSER IV, offsets will be input entries and analysts will be able to use the program as a simulation tool.

PASSER IV determines the best cycle length, signal splits, signal offsets, and signal phasing sequences. Two versions of the program are available: the standard version can handle networks having up to 20 arterials and 35 intersections, and an advanced version can handle even larger networks and is twice as fast as the standard version. A user-friendly graphic interface makes the program extremely easy to use. The features available in the current version include simultaneous maximization of uniform progression bands on all arterials in a network; arterial and directional priority options; determination of signal splits, optimal cycle lengths, optimal offsets, and optimal NEMA Phasing Sequences with overlap; and variation in link-to-link speeds.

The input used by PASSER IV includes optimization data and run options, network geometry and user-selected movement numbering schemes, and traffic data. The traffic data inputs include approach length, average speeds and range of speeds for all approaches, queue clearance times, traffic volumes, saturation flow rates, minimum green splits, green splits, and a cycle length range.

Model output includes summarized input, warning and error messages, an optimization performance plot, optimization statistics, and a solution report. The solution report contains a network-wide summary, with optimal cycle length and progression bands; a summary for each arterial, with efficiency, phase sequence, phase settings, travel times, speeds, and time space diagram; and a signal-by-signal solution, with NEMA phases and phase durations, and MOEs - delays, v/c ratios, and levels of service. The *PASSER IV- 94 Version 1.0 User/Reference Manual* (*10*) contains a detailed discussion of this program.

2.7 TRANSYT-7F

Dennis Robertson of the Transport and Road Research Laboratory in England developed the Traffic Network Study Tool. The University of Florida modified Version 7 for the Federal Highway Administration to reflect North American nomenclature . Analysts can use the program for the analysis and optimization of signal timing on coordinated arterials and grid networks. Features include provisions for actuated and pretimed control, the capability of modeling permitted left-turn movements, and provisions for including stopped controlled intersections along the arterial network. TRANSYT estimates MOEs for each of the movements at individual intersections, as well as overall MOEs for the arterial street network. The MOEs used by the program include delay, queues, stops, fuel consumption, total travel, total travel time, average travel speed, and total operating cost. Please refer to *The Methodology for Optimizing Signal Timing: MOST Reference Manual, Volume 4, TRANSYT-7F Users Guide* (*11*).

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; and evaluation of a specified range of cycle lengths determines the best cycle length. TRANSYT has given reliable signal timings when used with realistic input data, but the program does not always provide the absolute optimal solution.

TRANSYT-7F performs the optimization of cycle lengths by minimizing the Performance Index (PI), which is a linear combination of delay, stops and queue lengths. A "hill-climbing" optimization process is used to select the phase length that minimizes the PI. The optimization procedure in TRANSYT-7F begins with the initial signal timing plan input by the user or the program may generate initial offsets and phase lengths. Simulating traffic flow determines the PI for this initial timing plan. Offset alterations at the first signal continue as long as the PI is reduced. The model proceeds sequentially through all signals for all variations of the offsets and phase length inputs, attempting to locate a minimum PI.

The data required by TRANSYT-7F fall into four general categories: network data, signal timing parameters, geometric and traffic data, and control data parameters. The network data requirements for TRANSYT-7F include the identification of intersections and the approaches and movements at that intersection. The distance between intersections is also required as well as the existence of bus routes, parking, and turn restrictions. The signal timing parameters required by TRANSYT-7F include the following data: cycle lengths, offsets, phase sequences, interval durations, and the minimum phase durations. The traffic volume data requirements include: control volume counts, total flow by link and by movement, flow from mid-block sources, input flows from upstream links, and the classification of traffic. An input processing program known as EZ-TRANSYT facilitates input data entry into the model.

There are eight types of outputs provided by TRANSYT-7F including: an input data report, a traffic performance table, controller timing settings, stopline flow profile plots, time-space diagrams, a cycle length evaluation summary, a route summary report, and special outputs. The results of the simulation or optimization performed by TRANSYT-7F are summarized in a

Traffic Performance Table which reports various MOEs of traffic performance. For each link of the network the outputs produced are: link number, total traffic flow, saturation flow, degree of saturation, total travel, total travel time, uniform travel time, uniform delay, random delay, total delay, average delay per vehicle, uniform stops, maximum back of queue, queue capacity, fuel consumption, and the phase length. Included in the TRANSYT-7F MOEs is a Performance Index (PI), a linear combination of delay and stops which is minimized when producing the best signal timing plan.

2.8 TRANSSIM II™

TransSim II™ is a program developed by JRH Transportation Engineering of Eugene, Oregon. The program is microscopic with respect to LRT (or bus) behavior and movement within the modeled system and macroscopic with respect to traffic performance. The computation of MOEs for traffic is accomplished within TransSim II™ using a methodology similar to that found in the TRANSYT program.

Inputs to the program include features of the roadway environment (e.g., geometrics, traffic volumes, and signal phasing) and information about the transit route (e.g., including stations and intersections). Operating speeds and station dwell times can vary to better simulate realistic transit operations. The user enters data in a pull-down menu format under the entries of system data, route data, link data, and signal data. A variety of types and degrees of priority are available and easily selected by the user, facilitating the evaluation of alternative control strategies for the networks. For further information, refer to the *TransSim II™ Data Input Instructions* (*12*).

As with NETSIM, the networks are best conceptualized as nodes (intersections) and links (directional roadways). The physical and traffic operational features of the network are defined through link data, including traffic volumes and intersection spacing. The data describing the LRT route includes the number and location of stations within the system and the manner in which the LRT interacts with each station and intersection. Unlike NETSIM, links in TransSim II™ are organized as movements that move concurrently during a given signal designation. Movements which have exclusive lanes or bays, move in a unique set of phases, or have left turns that move under permitted phasing and occupy shared lanes must be coded as separate links. TransSim II™ uses the NEMA standard dual-ring numbering system for all traffic signal phases. Additional information coded into the model includes general system-wide data, such as LRT operational parameters and traffic system constants.

2.9 NETSIM

The NETSIM network simulation model (*13*) performs a microscopic simulation of traffic flow in an urban street network. The traffic engineer and researcher can apply the model 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, precluding the need for detailed calibration if such data has not been assembled.

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 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 input data requirements in NETSIM can be broken down into two groups: location specific inputs and network-wide inputs. The location-specific inputs characterize the network link and/or intersections. Some of these inputs include intersection discharge rates, input flow rates, intersection turning movements, traffic composition, pedestrian flows and delays, amber phase behavior, network geometry, and signal timing. The network-wide inputs remain constant across all links within a network. Some of these inputs include vehicle generating and gap acceptance distributions as well as parameters in the car following model, lane switching and intersection movement routines.

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. Input into the model is achieved through the use of "cards," each of which designates a particular type of input. Some general categories of card type include data set descriptor, run control, output format and frequency, link name, link characteristic, link-permitted movement, node signal timing and approach, node-permitted movement by signal phase, and end of input delimiter cards. Special bus cards can simulate bus lanes and routes, bus stations and station locations, and bus headways and dwell times. For advanced NETSIM simulation, special input cards can modify the default values used in the model to describe such traffic environment parameters as start-up lost time and queue discharge headway.

NETSIM has been applied to LRT simulation in the past. NETSIM was used (*14*) to evaluate the relationship between an intersection crossing volume and the average automobile delay at an isolated crossing. In NETSIM, the LRT was modeled as a single-lane roadway and the grade crossing as a two-phase, fully actuated intersection. The LRV's arrivals were modeled as buses operating on the track using specified headways. The model, however, gave unconditional priority to the LRT vehicles and made no allowances for nearby signals and progression (*14*).

Simulation of DART's North Central Light Rail Line was accomplished using a modified version of NETSIM (*15*). The original software did not readily accommodate the complex, frequently changing signal sequences found in the "window" limited priority scheme proposed for the DART line. Analysts identified restrictions in NETSIM that limited the signal transition flexibility and mitigated their influence on the simulation. NETSIM was used, in conjunction with TRANSYT-7F and the HCS (Highway Capacity Software), to identify the delay impacts of LRT and the presence, if any, of residual queues after LRV passage.

3.0 ANALYTICAL PROCEDURE

3.1 OVERVIEW

The recommended procedure for determining the operational impacts of at grade LRT crossings requires the analyst to select from a number of microcomputer traffic analysis tools. Based on a combination of crossing and environment type and the complexity of the situation being analyzed, the analyst selects a model to perform the analysis. A fundamental tradeoff in this model selection process is that those models which are easier to code also do not provide as detailed an analysis and as many options for output. The simpler models also do not tend to deal as well with complex operating scenarios and oversaturated conditions as the more complex models. The analyst must consider the use for which the results are intended (i.e., simpler models for planning level and general operations analysis, and complex models for traffic engineering and detailed operations analysis), the accuracy of the data input into the models, and the desired level of data entry and coding effort.

If the system currently exists and alternative control strategies are being analyzed, descriptive information about the roadway and LRT network are collected and entered into the model. The analyst then calibrates the model to field conditions based on further collected field data and performs the analysis. If the system is a proposed system, the network data must be taken from projections of traffic after LRT implementation, the proposed alternatives for system geometry, and signal settings that are produced by mathematical methods or computerized optimization tools. The analyst codes and calibrates the model using recommended values and field data from the proposed implementation sites and performs the analyses. Outputs should not be compared across models. Each model processes input information differently and, if two models are used, it would be difficult to differentiate between genuine differences in system performance and differences between models. If two or more models are used, all cases - including the control case without LRT - should be analyzed with each model and output only compared with output from the same model.

A check is included in the procedure to monitor the modeled system for failures. Queues that spill back into upstream intersections or intersections where demand exceeds capacity warrant special consideration and possible redesign. After the analyst performs all analyses and checks the output, he/she converts the MOEs from the programs to user costs and selects the preferred alternative.

Throughout the process, it is essential that the analyst exercise good engineering judgement and document all analyses. Organized records are the only means of associating sets of input data with the correct alternatives and assumptions, and, ultimately, the appropriate outputs. Scale drawings or schematic maps of the sites under investigation are necessary to familiarize the analyst with the features of the network and identify those locations in the network where queuing in the system will have deleterious impacts on traffic performance. Such problem locations include short block lengths or short intersection spacings, high volume access driveways, and left turn bays.

The stepwise procedure is organized according to the flowchart (Figure 1) on the following page and each step is documented in next section of this report (Section 3.2).

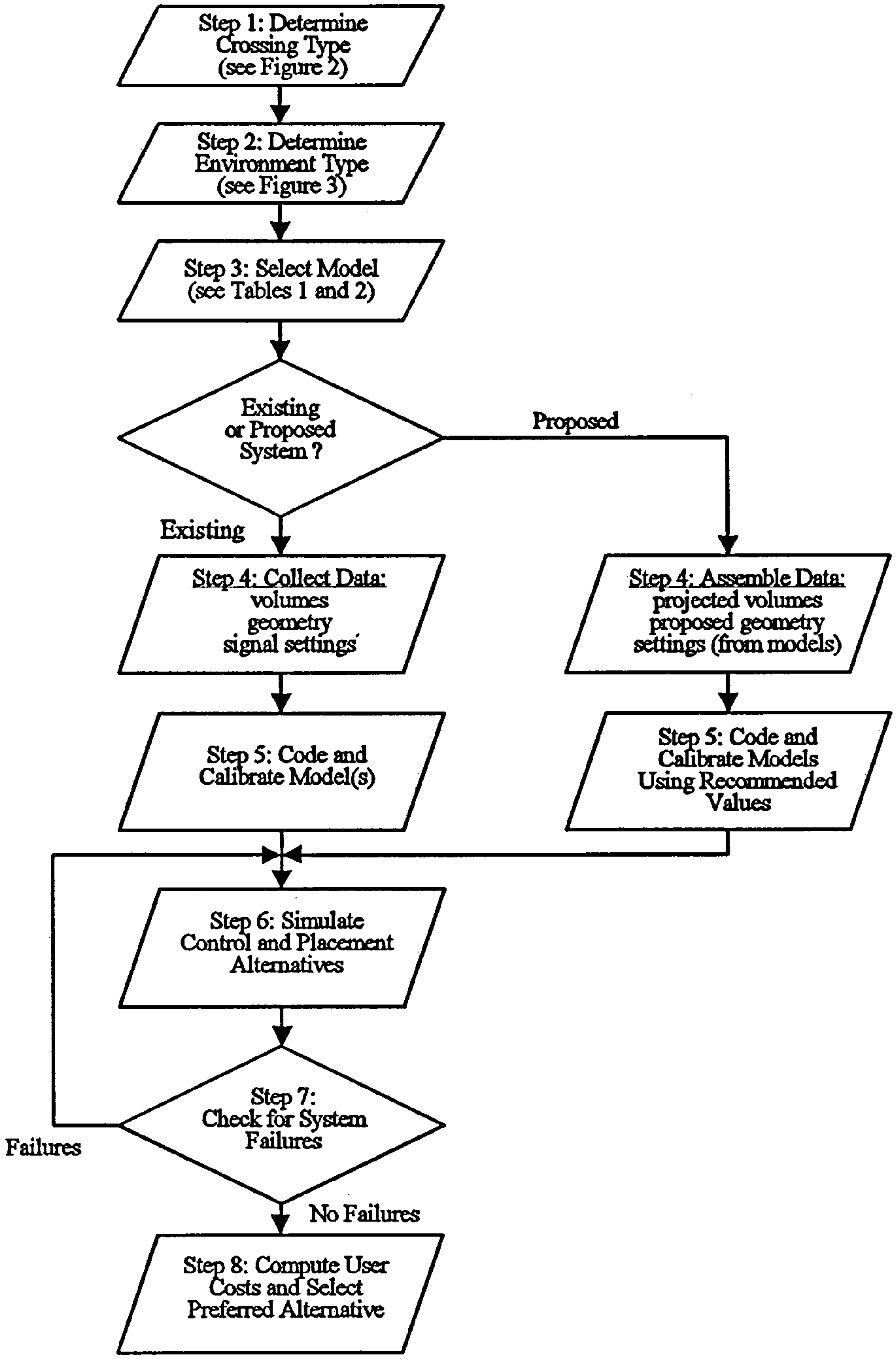
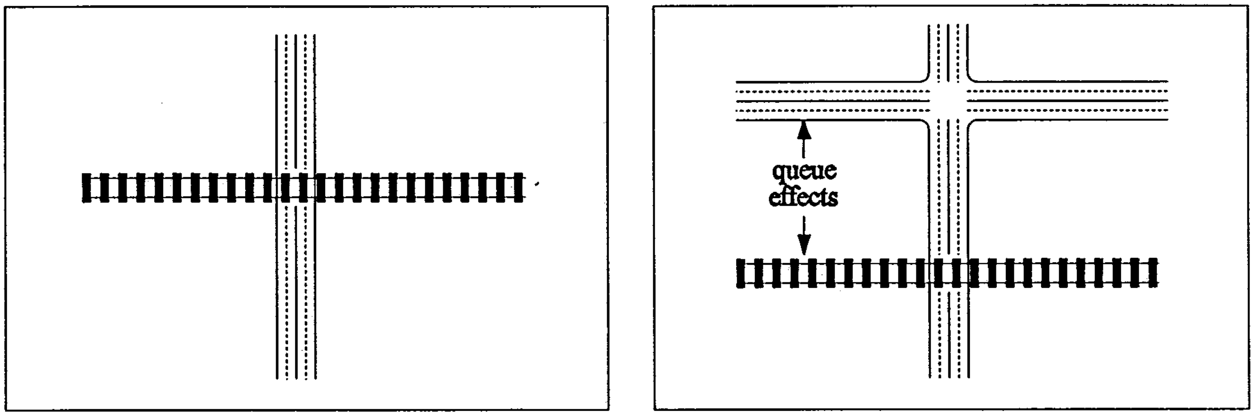


Figure 1. Analysis Flowchart for LRT At Grade Crossings

3.2 STEPWISE ANALYSIS

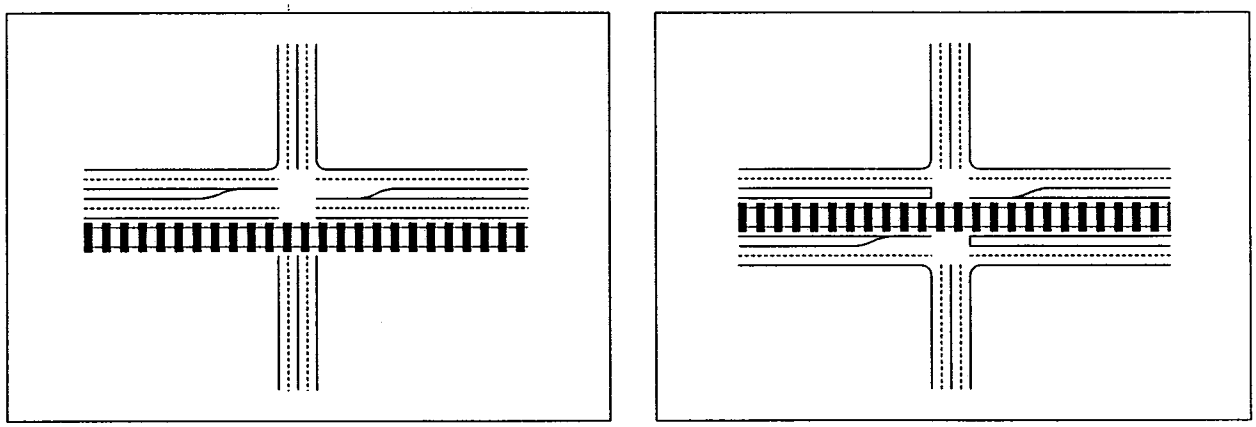
STEP 1: Determine Crossing Type

Four major at grade configurations exist for LRT-roadway intersections: isolated crossings, isolated crossings with a nearby traffic control device, crossings where LRT is adjacent to a parallel street, and crossings for LRT median operation (*16*). For each type of crossing, there are modeling concerns such as the presence and handling of turning vehicles, the need to prevent cross street vehicles from encroaching on the LRT tracks (crossing spillback), the degree of priority needed for LRVs, the optimal signal timing, and the effects of altering the signal timing for an LRV when the signal is timed for arterial progression. Visual outlays of each type of crossing can be found in the figure below. An isolated LRT crossing is considered "near" a signal when the nearby intersection is within 122 meters (400 feet) of the crossing (*14*).



Isolated Crossing

Isolated Crossing near Signal



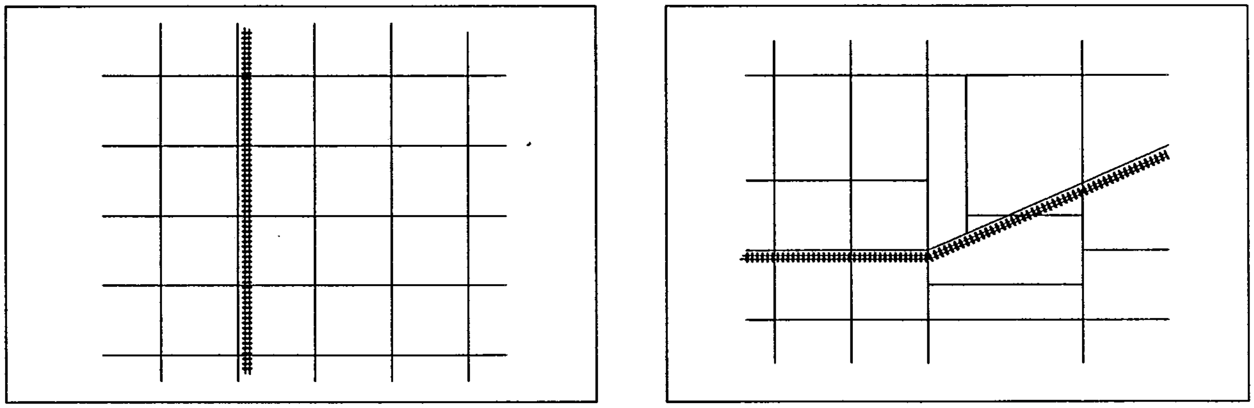
Crossing Adjacent to Parallel Street

Crossing for LRT Median Operation

FIGURE 2. Types of LRT Crossings

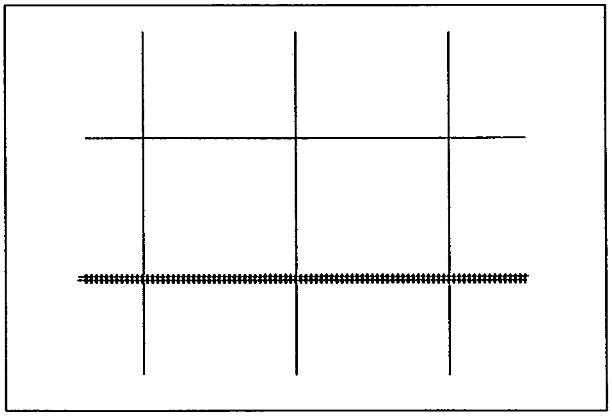
STEP 2: Determine Environment Type

LRT right-of-way and environment describe the purpose and exclusivity of the corridor in which the LRT line is or will be located. The land on which the line will be constructed may be devoted entirely to the transit facility and its appurtenances, it may be shared with a freight rail line, or it may even be in the right-of-way of a municipal street. Within the corridors, varying at grade LRT track placements have been utilized in cities around the country. 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 since there are many predominantly at grade LRT lines that are grade separated at intersections where a high degree of automobile congestion exists. This issue has been addressed for LRT (*17*). An additional environmental factor is the type of urban area through which the LRV will run. Categories for differentiation of area type, as shown in the figure below, are downtown areas, areas with tight street grids, and areas with widely spaced arterial crossings.



LRT in Grid Network

"Downtown" System



Widely Spaced Arterials

Figure 3. Types of LRT Urban Environments

STEP 3: Select Model

Model selection for analyzing LRT alternatives is based on numerous factors. Primary among these factors are the geometry of the crossing or network being analyzed, the type of control present or proposed, and the function the model will fill in the analysis. Tables 1 and 2 categorize the models to some extent, but it is ultimately the responsibility of the analyst to become familiar with the applications and limitations of the programs recommended for the analysis.

Table 1 identifies the analytical functions, control functions, and geometric conditions that the models were designed to analyze. For analytical functions, the models can either (1) evaluate-- use existing conditions and mathematical formulations to generate MOEs to describe the system; (2) optimize --produce signal settings that minimize delay or a combination of MOEs; or (3) simulate - emulate an existing or proposed set of conditions and generate descriptive MOEs. Control function identifies whether the model can analyze pretimed or actuated control. Currently, only TransSim II™ can directly model priority schemes for transit - especially partial LRT priority simulation. Model application to individual intersections, corridor situations, or networks is specified under analysis tool geometry.

Certain analysis tools, by their nature, are more adept at handling some types of problems than others. Table 2 lists which programs are recommended for combinations of LRT environment type and crossing type. In general, the farther the program is down on the list within a box of the matrix, the more complex the program. Also, the more complex models tend to require more coding effort and more types of input than the simple models. NETSIM will most likely produce the best results for oversaturated conditions, should the modeled network be near or over capacity.

Table 1. Model Applications and Functionality

Model	Analytical Function (E)valuation (O)ptimization (S)imulation	Control Function (L)RT Priority (A)ctuated (P)retimed	Geometry (N)etwork (C)orridor (I)ntersection
HCS	E	P	I
PASSER II	E, O	P	C, I
TEXAS	S	A, P	I
EVIPAS	S, O	A, P	I
PASSER IV	E, O	P	N, C, I
TRANSYT-7F	E, O	P	N, C, I
TransSim II™	S	L, A, P	N, C, I
NETSIM	S	A, P	N, C, I

Table 2. Model Selection Matrix

Crossing Type	Environment Type		
	Downtown	Grid	Widely Spaced
Isolated			HCS PASSER II TEXAS EVIPAS TransSim II™ NETSIM
Isolated w/ nearby signal	TransSim II™ NETSIM	TransSim II™ NETSIM	TransSim II™ NETSIM
Side of Street	TRANSYT-7F TransSim II™ NETSIM	TRANSYT-7F TransSim II™ NETSIM	HCS EVIPAS TRANSYT-7F TransSim II™ NETSIM
Median	PASSER IV TRANSYT-7F TransSim II™ NETSIM	PASSER IV TRANSYT-7F TransSim II™ NETSIM	HCS PASSER II TEXAS EVIPAS PASSER IV TRANSYT-7F TransSim II™ NETSIM

STEP 4: Assemble Simulation Data

Traffic, Geometric, and Signalization Data

Since the data is being collected as input data for models being used to simulate and evaluate LRT crossings and networks, the data that must be collected is defined by the data requirements of the models. The following list summarizes the necessary input data for the models:

1. Link geometry: length in feet, grade in percent, saturation flow rate in vehicles/hour;
2. Operational data by link: number of travel lanes, target speed, queue discharge rate, start-up delay, pedestrian volume, lane use;
3. Turning movements by link: number or percent of vehicles proceeding straight or turning at the downstream end of a link;
4. Signal controls by intersection: signal offset in seconds, phase length in seconds, and control for each approach during each phase; and
5. Flow rates by source link: peak hour volume that is emitted from each source node in number of vehicles.

An efficient means of formatting the model input data is by using the *Highway Capacity Manual* Input Worksheet (*5*). An example of this sheet can be found in Appendix A. It is important for each sheet to be completed in full for each intersection, including an accurate sketch representation of the number of approach lanes, lane usage, lane widths, and turn bay presence.

Additional input information includes the following:

1. The signal offsets between intersections, which can be noted on the HCM worksheet and referenced to the upstream intersection;
2. The link lengths, measured from the stop bar at one intersection to the stop bar at the downstream intersection. These measurements must also be made at the intersections of roadways with LRT lines; and,
3. The frequency of LRV arrivals (headways), type of signal control implemented when LRV arrives at the intersection, location of stations, and average dwell times.

LRT Operations

To ensure accurate representation of the LRV within the model, it is necessary to provide accurate information about the vehicle's features and operations. These items include LRV characteristics, which are listed in Table 3; headways, or the average time between LRV arrivals, for LRT operations in some United States and international cities (shown in Table 4); dwell time, or the time required for passenger boarding and alighting, which is nominally 20 seconds but may be extended up to one minute for handicapped passengers; and operating speed, which can be as low as eight to sixteen kilometers per hour (five to ten miles per hour) in pedestrian malls and as high as 90 to 100 kilometers per hour (55 to 60 miles per hour) in exclusive right-of-way. In most urban environments that are under LRT non-priority or partial priority operation, it is necessary for LRVs to use the speed of arterial street progression similar to automobiles, often between 50 and 65 kilometers per hour (30 to 40 miles per hour).

Table 3. Typical LRV Characteristics

Characteristic	Value
Maximum Acceleration	4.8 kph/s (3 mph/s)
Maximum Service Braking Rate	4.8 kph/s (3 mph/s)
Maximum Emergency Braking Rate	9.7 kph/s (6 mph/s)
Length	18 to 29 meters (60 to 95 feet)
Width	2.4 to 2.8 meters (7.9 to 9.3 feet)
Minimum Turning Radius	12.8 to 25 meters (42 to 82 feet)

Table 4. Minimum LRT Headways by City

City	Minimum Headway minutes	Speed at Crossings kph (mph)
Boston, MA	5	24-32 (15-20)
Buffalo, NY	5	24 (15)
Calgary, Canada	2.5	40-80 (25-50)
Cleveland, OH	4	40-64 (25-40)
Edmonton, Canada	5	60 (37)
Los Angeles, CA	6	varies
New Orleans, LA	4	16 (10)
Newark, NJ	2	32 (20)
Philadelphia, PA	3	48-80 (30-50)
Pittsburgh, PA	3	16-24 (10-15)
Portland, OR	7.5	24-56 (15-35)
Sacramento, CA	15	56 (35)
San Diego, CA	15	40-80 (25-50)
San Francisco, CA	3	16 (10)
San Jose, CA	5	16-56 (10-35)
Toronto, Canada	2.5	16 (10)

Traffic Control Devices

Pursuing the discussion of LRT roadway crossings, another topic to be addressed is the type of control present at the crossing. The crossing may exhibit crossbucks only, flashing lights with crossbucks, flashing lights with gates and crossbucks, or standard traffic control devices (*16*). Each control option has different blockage, clearance, and lost times, and all differences must be accounted for as accurately as possible within the model. In some cases, the analyst must consider a different time, such as the gate "down" time at a gate controlled crossing or the time required by a regulatory agency (i.e., the 20 second gate down time before train arrivals required by the California Public Utilities Commission), for impacts on associated phases.

Table 5 contains LRT lost plus clearance time values for standard, signal controlled intersections for different crossing roadway widths. For the table values, lost time is assumed equal to 2.5 seconds and LRT acceleration from a stop is 1.3 meters per second^2 (3 mph/s).

Table 5. LRT Lost Plus Clearance Times

Crossing Roadway		
Number of Lanes	Approximate Width meters (feet)	Lost + Clearance Time sec
2	8 (25)	6
4	15 (50)	7.5
6	23 (75)	8.5

Table 6. Blockage Times for At Grade Crossing Control Devices

Device	Warning Time (sec)	Nominal Total Blockage Time (sec)
Crossbucks only	5	13
Flashing Lights	20	28
Flashing Lights with Gates	15	35
Standard Traffic Signals	5	13

Table 6 contains average expected total blockage times for various crossing control devices. Passively controlled crossings are assumed to have a five second (*18*) warning time, which is the time between the initialization of crossing control device function (i.e., the recognition of a sign or the activation of an active control device) and the arrival of the LRV at the crossing. Flashing lights are activated at least 20 seconds before train arrival (*19*); and, at gated crossings, the flashing lights activate three seconds before the gate begins to drop, an action which takes between 9 and 12 seconds. At crossings controlled by standard traffic signals, warning time is vague in definition, but can be considered as the yellow plus all red time (usually about 5 seconds, but increased if the clearance is needed) of the phase terminating before the phase associated with LRV movement begins. Nominal total blockage times are computed as the sum of the warning time, the time the LRV physically occupies the crossing, the time between the departure of the LRV and the time the warning device ceases operation, and the lost time to vehicles receiving the right of way after the LRV passage. Assumptions in the calculations include an LRV length of 190 feet (two car consist), an average LRV speed of 13.5 m/s (30 mph), a crossing width of 4 lanes, 12 seconds to raise gates, and a lost time of 2.5 seconds. The total blockage time will change significantly for different LRV lengths, speeds, and intersection widths.

Control Strategy

In addition to the reproduction of the physical aspects and features of the modeled environment, it is also necessary to incorporate the control strategy found in the network. Where LRVs and automobiles are considered equally, no modifications are required; however, where transit is given special treatment, signal priority for the LRV must be considered in the model.

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 at the intersection. McGinley (*20*) provides an extensive discussion on both passive and active priority techniques. Passive priority treatments use anticipated public transit operations to determine the required priority treatment to be implemented. Treatments that fall into this category include:

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

Active priority treatments improve upon one basic weakness in passive priority treatments, and that is their ability to sense the presence of the public transit vehicle and select the most suitable priority technique. Common active priority techniques are listed below:

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

The most appropriate method of modeling priority phasing will vary by the type of priority implemented or proposed for implementation and the model selected for the simulation. Fortunately, all controllers provide the same basic priority/preemption sequencing (*21*):

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

STEP 5: Code and Calibrate Model(s)

HCS

The HCS signalized intersection section is appropriate for modeling uncongested, isolated crossings or intersections (isolated, side of street, or median LRT) operating under pretimed signal control. At isolated intersections, the HCS should be coded as usual for traffic. The only additional consideration is ensuring that the phase length entered for the phase or phases associated (non-conflicting) with LRT movement is at least as long as the LRT lost plus clearance time. Values for LRT lost plus clearance times can be found for varying conditions in Table 5 of this report. Calibration adjustments to traffic flow can be made through the entries for saturation flow rate. Field measurements of departure headways or default values of the HCS model are common sources of saturation flow rate values.

It is unlikely, though possible, to find an isolated LRT crossing that does not employ some form of LRV sensing, such as railroad block sensing and preemption, to control the crossing. Such a crossing may simply be controlled by crossbucks and stop signs at the two vehicular approaches. With limitations, the HCS can be used to determine traffic MOEs at the crossing. When using the HCS to model isolated LRT crossings, the headway of arriving LRVs is the driving factor in the analysis. Traffic and LRVs essentially consume portions of the "green" time for the analysis period at the crossing. The analyst enters the appropriate blockage time for the control device at the crossing as the cross street phase (phase five) green in the HCS, and the rest of the green is for the roadway. Phase length in the HCS ranges from 0 to 99 seconds for the green and 0 to 99 seconds for the yellow plus red clearance time (still counted as green time by the HCS). Since there are four main street phases, each including green and yellow plus red times, the maximum LRT headway analyzed using this method is about 13 minutes. Again, the delay values are valid only for traffic.

Since the HCS computes such traffic parameters as saturation flow rate from input data, no additional calibration (aside from the usual data entry process) is necessary. It is unlikely that at an isolated crossing there would be no type of detection and control equipment for transit. For modeling traffic and/or LRT actuated intersections and actuated crossings, microscopic modeling (TEXAS, EVIPAS, TransSim II™, NETSIM) is recommended.

PASSER II

PASSER II can be used to evaluate and optimize pretimed, uncongested, non-priority signal operations at isolated LRT crossings or intersections with median running LRT that exist individually or in a series along an arterial. For some single intersection applications (nearby crossing and side of street LRT), PASSER II is not appropriate since the model can only consider one cycle length at a time and cannot analyze right-turn movements that occur separately from through movements. As with the HCS, the input and output procedure follows the same steps as the standard traffic data entry. When modeling isolated LRT crossings using PASSER II, the output MOEs apply only to network traffic. When modeling median running LRT at widely spaced, uncongested intersections (or series of intersections) under pretimed control, the output applies to both traffic and LRT.

Modeling isolated LRT crossings in PASSER II requires coding green at the crossing equivalent to the average existing or anticipated headway of LRVs arriving at the crossing. The average blockage time is entered on the two approaches for LRVs and the remaining portion of the headway (time between LRV arrivals minus blockage time) is entered as green time for the roadway. Average blockage time values are linked to the type of control present at the crossing and the jurisdictional regulations governing crossing control. Table 6 contains some point-of-reference values for blockage times occurring with different crossing control devices.

To model isolated intersections (or series of intersections) with median running LRT under pretimed control, PASSER II is coded as usual for traffic. Entering the Table 6 value for standard traffic signals as the minimum green for the phase ensures adequate green time for LRV passage during the associated traffic through phase. When evaluating and/or optimizing a series of such intersections along an arterial, this minimum applies to the phases associated with LRV movement at each intersection. The analyst can make calibration adjustments to traffic flow through the entries for saturation flow rate. Field measurements of departure headways, default values of the PASSER model, or the HCM (*5*) are sources of saturation flow rate values. Since the LRVs approaching each intersection from both directions are subject to the same signal indications (except under lead-lag phasing) as the through vehicular movement, the MOEs for associated phase traffic also apply to LRVs. Complicating factors at these intersections, such as LRT stations near an intersection, will impact the computed MOEs but cannot be modeled in PASSER II.

TEXAS

The TEXAS model applies to the simulation of isolated LRT crossings or pretimed and/or actuated intersections with median-running LRT. Detectors applied to simulated crossings emulate crossing control device behavior, but at intersections the approaches are consumed by traffic (no means are available to physically model LRT) and only non-priority LRT median operations can be modeled. In this manner, MOEs for parallel street through vehicles are used as a proxy measure of LRT performance at the intersection.

For individual isolated crossings, the geometry consists of four legs, two for two-way traffic and two for two-way LRT. The crossing is coded as a semi-actuated crossing, where the detectors are located on the two LRT approaches. The crossing control device blockage time from Table 6 is entered as the actuated phase initial interval (extendable for an LRV approaching from the other direction in two-way operation) for LRT. The phase for the traffic approaches is a minimum walk or vehicle time to cross the tracks for a phase that is set on recall. The vehicular green is then only interrupted by the approach of an LRV. Once coded, the detector placement may need to be adjusted in an iterative trial-and-error process to produce a simulation of realistic LRT operations. MOEs from the simulation are valid for traffic and LRT. It should be noted that this phasing structure provides unconditional priority for LRT-- a worst case scenario for automobile traffic.

Non-priority operations of median-running LRT can also be simulated using TEXAS. The model is coded as usual for traffic, geometric, and signal conditions. It is also necessary to enter a minimum parallel street through phase that is at least as long as the blockage time for the desired intersection control device for LRT, shown in Table 6. The output directly applies only to traffic, but the delays to parallel street through vehicles can also be used to monitor LRV performance at the intersection, especially if the green time for through vehicles is equal to the green available to LRT (parallel street left turns are both leading or lagging, permitting the entire through phase to be associated with LRT movement).

EVIPAS

EVIPAS can be used to model isolated LRT crossings and intersections where LRT operates in the median or on the side of the street. Signal information is coded into the model in a modified NEMA format and the moving lanes by phase can be specified. With this option and the ability to code the percentage of through traffic in each approach lane, EVIPAS has the flexibility to evaluate and optimize a variety of pretimed and actuated signal strategies.

At isolated crossings with flashing lights or flashing lights and gates, the presence of an approaching LRV triggers the crossing control device. In EVIPAS, the analyst models this behavior by coding the crossing as an intersection with the traffic approaches on recall and the LRV approaches fully actuated. Traffic will receive the right-of-way except during the crossing of an LRV, and the duration of the traffic interruption is the time, linked to crossing control device, provided in Table 6. Some iteration is required to position LRV detectors an appropriate distance from the crossing so that the traffic control device can be activated and vehicles can clear the crossing before the arrival of the LRV. In addition, the actuated phase called by the LRV should be extendable to simulate realistic rail operations under two-way LRV passage. MOEs for both traffic and LRT are available from the simulation and/or optimization. It should be noted that this phasing structure provides unconditional priority for LRT - a worst case scenario for automobile traffic.

Individual intersections where LRT is located in the median or on the side of the street can be coded for pretimed signal operation and operation where LRVs receive right-of-way concurrently with traffic-actuated movements. EVIPAS cannot be used to simulate priority strategies for LRT at intersections since the approaches to the intersection have been coded for traffic. For simulating LRV detection with priority at intersections, TransSim II™ or NETSIM should be used.

After coding EVIPAS as usual for the given intersection geometry, volumes, and signal settings, the only adjustment for simulating the intersection under LRT operation is ensuring that the minimum green for phases associated with LRT movement is at least as long as the LRT blockage time. Table 6 provides blockage time values for the various control devices. Special attention is necessary when analyzing side of street LRT operations since right turns on the street at driveways and intersections, a normal feature of roadway operations in most locations, cause conflicts with LRT movement. When modeling side of street LRT using EVIPAS, the phasing must be structured such that green time is allotted to right-turning vehicles separately from the LRVs, while both occur with parallel street through traffic. This phasing pattern is possible through assigning the right lane of the roadway for right turns only and permitting this lane to move before or after an interval during which only the parallel street through movements (associated with LRV movement) occur. Calibration adjustments to traffic flow can be made through the entries for saturation flow rate. Saturation flow values can be obtained from field measurements of departure headways, default values of EVIPAS, or the HCM (*5*). MOEs from EVIPAS for intersections are valid only for traffic.

PASSER IV

Median-running LRT in downtown, grid, or widely spaced pretimed intersections can be optimized using PASSER IV. In PASSER IV, only non-priority systems with LRT movements associated with parallel street through movements can be analyzed. In all LRT applications, the model is coded as usual for traffic and then checked to ensure that the minimum duration of the phase associated with LRT movement is equal to or greater than the blockage time for the type of traffic control device existing or proposed for the intersection(s). Entries for saturation flow rate allow for calibration adjustments to traffic flow. Field measurements of departure headways, default values of the PASSER IV model, or the HCM (*5*) are sources of saturation flow values. Blockage time values are found in Table 6. MOEs generated for the optimized network or intersection apply to both traffic and LRT, where the average delay for parallel street through traffic is also representative of the average delay for LRVs (in the absence of transit stations near the intersections).

TRANSYT-7F

TRANSYT can be used to evaluate and optimize a variety of pretimed and actuated, non-priority crossing and environment types. Though TRANSYT applies to many network study problems, there are limitations that impact its use for LRT analysis. The inability to code cycle lengths longer than 300 seconds limits LRT movement in the model to environments where phases are associated with LRT (side of street and median LRT operation) movement. This limitation is enforced by the constraint that TRANSYT can only optimize to one cycle length for a given network. Separate nodes (isolated crossings) coded for LRT would operate at the network optimum cycle length, though this cycle length does not apply to LRT operations, where the headway of LRVs determines the temporal interruption of traffic flow. Finally, given the macroscopic nature of TRANSYT, it is recommended that detailed simulation of actuated control and queuing be accomplished using NETSIM.

Side of street and median LRT is evaluated and/or optimized with TRANSYT by coding the model in the usual form for traffic and ensuring that the phases associated with LRT movement have a green duration greater than or equal to the blockage time in Table 6 for the desired control device. Entries for saturation flow rate allow for calibration adjustments to traffic flow. Field measurements of departure headways, default values of the TRANSYT model, or the HCM (*5*) are sources of saturation flow values. MOEs generated for the optimized network or intersection apply to both traffic and LRT, where the average delay for parallel street through traffic is also representative of the average delay for LRVs (in the absence of transit stations near the intersections).

TransSim II™

TransSim II™ can be used to simulate all of the environment and crossings type combinations in the Model Selection Matrix (Table 2). It can analyze pretimed and/or actuated control and is the only model reviewed with the ability to directly model the impacts of different types of LRT priority. The traffic model in TransSim II™ is macroscopic and similar to that found in TRANSYT, but LRT is modeled on a microscopic basis.

Following the entry of the input geometric, traffic volume, and signal timing data, few adjustments were required in order to run the model. Several of the inputs, including entries for LRV acceleration and deceleration, start-up lost time, average speeds for LRVs and automobiles, and the standard deviation of LRV entry into the modeled system, enabled adjustment of the model's environment parameters to field conditions. Calibration adjustments to traffic flow are possible through the entries for saturation flow rate. Saturation flow values can be obtained from field measurements of departure headways, default values of the model, or the HCM (*5*). The one model parameter that did require adjustment through iterative runs of the program was the location of the detector that notified the downstream intersection of an approaching LRV in the priority networks. This distance was nominally the braking distance of the LRV plus any remaining distance required to produce the time equivalent of the minimum phase duration on the cross street.

Accurately modeling LRT in TransSim II^{TM} requires a number of information elements. Because the program is microscopic with respect to LRV behavior (i.e., the LRVs are tracked through the system and directly detected to receive priority calls), any physical or control elements that impacted the LRV must be identified and entered. This information included:

1. The location of the intersection along the LRT route;
2. The location of notification, commitment, and checkout detectors;
3. The automobile phase associated with train movement through the intersection;
4. Time-to-green when a call is placed at a notification detector;
5. Minimum phase durations for phases that could be shortened during priority calls;
6. The location and service times of stations along the route;
7. Scheduled headways for LRVs in the system;
8. The speed through the system, which could be changed along the route if variable speeds were found in the field;
9. LRV acceleration and deceleration rates; and
10. The type of priority and control found in the field environment, which could be varied from intersection to intersection.

NETSIM

NETSIM is capable of simulating all of the combinations of environment type and crossing type found in the Model Selection Matrix (Table 2). Though NETSIM cannot directly simulate priority phasing for LRT, nodes and phasing can be structured to model fully actuated phases (simulating full LRT priority) for LRT. Alternatively, the phasing impacts of a known or predicted LRT priority sequence can be coded into NETSIM using pretimed phase intervals that correspond to the controller's behavior under the priority phasing scenario. In this manner, traffic MOEs are available for priority schemes even though the schemes themselves are not directly modeled. Because NETSIM is microscopic with respect to simulated automobiles and LRVs, NETSIM fills the need for detailed simulation of actuated traffic control and reliable modeling of queue behavior and queue impacts.

Isolated crossings are modeled in NETSIM as actuated intersections. Links carrying automobile traffic are set to recall and the LRV approaches are coded with minimum green equal to the blockage times for the desired crossing control device found in Table 6. LRV phases should be extendable to account for successive arrivals in two-way operation. To ensure adequate crossing time for automobiles once an LRV phase has ended, a vehicular minimum crossing time should be entered for automobile phases. MOEs for this full LRT priority scenario are provided for both LRT and automobiles. The NETSIM algorithms for routing, headway, transit vehicle description, and stations for buses are recommended for use in coding LRVs into the model.

As an alternative to the essentially full priority scenario described above for LRT, isolated crossings can be coded using pretimed NETSIM signal cards. An average LRT headway can be selected and used as the background cycle length at the crossing. The blockage time (Table 6) is entered as the portion of the cycle for LRT and the remainder of the cycle length is for automobiles. The background cycle length can be varied using multiple time periods in NETSIM for stochastic influences on headway or to simulated increased/decreased LRV frequency. In this non-priority, isolated analysis, the MOEs only apply for automobile traffic. In fact, because the time impacts of LRV arrival are pretimed into the simulation, LRVs need not be coded in the simulation.

In environments where crossings are isolated but near a traffic signal, LRT operates on the side of the street, or LRT is found in the median of the street, modeling LRT necessitates creating separate nodes for traffic and LRT. Crossing roadway links join the traffic and LRT nodes just as the roadways they emulate perform this function in the field environment. Network structure of this form allows analysts to circumvent coding limitations in NETSIM, such as the restrictions that moving links (i.e., median running LRT) cannot be located to the left of left-turn bays and the maximum eight phases per intersection, which do not allowing phasing for LRVs if all eight phases are used for traffic. The proposed network intersection structures are illustrated below in Figure 4.

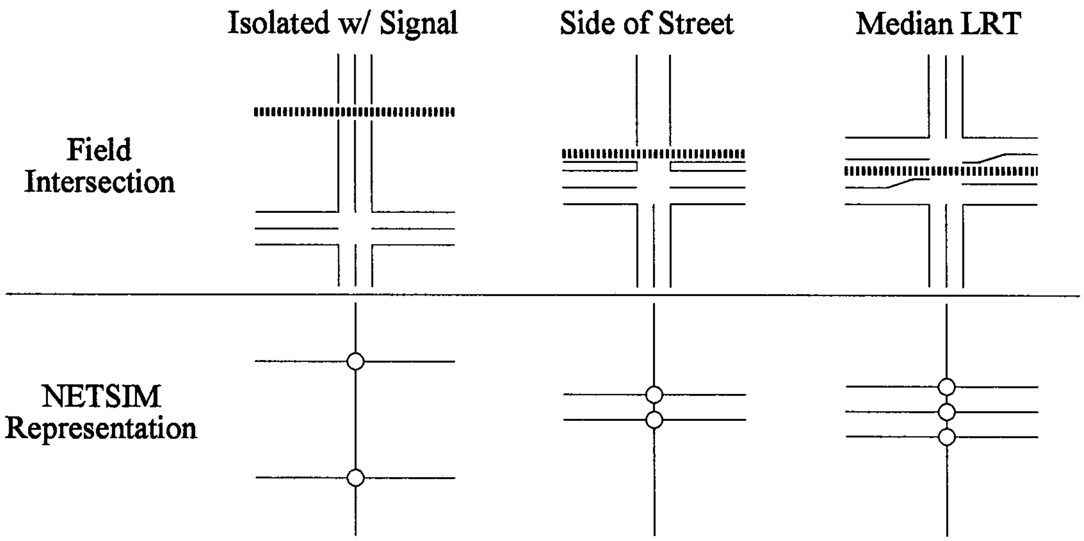


FIGURE 4. NETSIM Link-Node Structure of Field Intersections

As a result of coding intersections in the format recommended in Figure 4, roadway links are found in the model that are not found in the field. Also, the minimum link length requirement in NETSIM is 15 meters (50 feet), so intersections in the model for side and median running LRT may tend to be wider than their field counterparts. The impacts of this extra travel distance minimally impact the MOEs generated by the simulation (*2*).

Additional signalization benefits result from coding separate nodes for traffic and LRT when modeling semi-actuated and fully actuated networks with full LRT priority. Nodes for traffic display indications according to signal settings from the field and the LRT nodes display the minimums for cross street traffic and the average blockage times for the LRVs (Table 6). The LRT nodes dwell in cross street green and the LRVs, when detected, call for the green but do not violate cross street vehicular or pedestrian minimums. This system behavior replicates field conditions with two exceptions: (1) the 15 meter (50 foot) minimum link length between the traffic and LRT nodes allows traffic to queue in the interior and (2) the presence of an approaching LRV does not affect the controller for traffic. Thus, although the controller at the traffic node does not display a red signal indication to movements conflicting with approaching LRVs, this red is encountered when vehicles reach the LRT node. Also, the traffic node, not being linked to the LRT, could not be "knocked out" of synchronization and forced into a situation where it had to dwell in a specified phase to "resync" itself. Again, the MOE impacts of full LRT priority controller behavior using this multi-node simulation are minimal (*2*).

LRT can be modeled in NETSIM using bus routes. The location of the route is specified similarly to normal roadway links, but no traffic volume is entered for these links. Rather, bus routing is established using card type 187 and bus headways are specified using card type 189. Stations can be included using card type 185, which physically locates the stations in the network, and card type 188, which indicates the order in which the LRT will reach each station. One can even specify mean dwell times at stations and their distribution with card types 186 and 150, respectively. The length and acceleration properties of the LRT vehicle can be input, rather than those of the bus, using card type 58; however, the maximum vehicle length that one can enter is 38 meters (125 feet), while dual car LRT trains can be up to 54 meters (175 feet) in length.

Card type 11, one of the network descriptor cards, has three entries which are important in model calibration. The entries are the mean start-up lost time, mean queue discharge headway, and free flow speed. If the mean start-up lost time or queue discharge headway were lower, the vehicles that were stopped at one intersection would reach the downstream intersection sooner. If the mean values from the field differ from the defaults in the model, the observed means can be entered in the appropriate column of card 11. Not only can the mean values change, but their distributions can change as well. Any noticeable differences between model and field distributions can be brought into agreement by changing the start-up lost time distribution or mean queue discharge headway distribution in the model using card type 149. Free flow speed, which can be changed on card type 11, can also impact the time that platoons arrive at a downstream intersection since the higher the free flow speed entered, the higher the average speed along the link. Free flow speeds also follow a distribution, and this distribution can be changed using card type 147.

Other cards can be used to adjust other model parameters. The possible changes can impact turning speeds, lane switching, spillback probabilities, amber phase response, left-turn gap acceptance, pedestrian delay, short and long term events, parking, and a host of other parameters. Sufficient data cannot be collected to adjust all parameters, so the default values within NETSIM are normally utilized.

The model defaults for mean start-up lost time, queue discharge headway, and free flow speed are 2.5 seconds, 2.2 seconds, and 56 kilometers per hour (35 miles per hour), respectively. For each vehicle, the program uses the randomly assigned driver characteristic (1 = passive, 10 = aggressive) to select a multiplier from the distributions, shown in Table 7, to be multiplied by the mean start-up lost time or queue discharge headway to determine the specific value for that vehicle. NETSIM default values and values from field data collections are shown, but it is recommended that field data for these parameters be collected in the locations where LRT is or will be implemented.

Table 7. NETSIM Start Up Lost Time and Queue Discharge Headway Distributions

			Driver Characteristic, K									
	Network	Avg.	1	2	3	4	5	6	7	8	9	10
Lost Time	Default	2.5	218	140	125	118	102	86	78	63	47	23
Headway	Default	2.2	170	120	120	110	100	100	90	70	70	50
Lost Time	Los Angeles	1.88	145	124	114	105	101	96	92	83	74	66
Headway	Los Angeles	1.97	155	125	114	107	98	93	86	81	73	68
Lost Time	Los Angeles	1.88	145	124	114	105	101	96	92	83	74	66
Headway	Los Angeles	1.91	140	122	114	110	105	96	88	81	76	68
Lost Time	Long Beach	2.08	146	130	115	108	100	94	86	81	74	66
Headway	Long Beach	2.06	148	121	111	105	100	94	90	80	78	73
Lost Time	Portland	1.72	152	124	115	106	98	89	82	82	79	73
Headway	Portland	2.16	147	119	110	105	100	95	91	87	79	67
Lost Time	Portland	1.83	144	126	106	102	98	93	88	86	82	75
Headway	Portland	2.03	130	115	112	107	104	99	93	88	80	72

MOEs from most NETSIM scenarios are valid for traffic and LRT. Exceptions arise when modeling any type of priority impacts since NETSIM is not capable of modeling the control impacts of priority phasing. This phasing, once known, can be entered as phase changes during multiple time periods, but the MOEs would not be valid for LRT since the sensing of the LRVs does not produce phase strategy changes. An example of this is a window stretching algorithm in the field whose phasing impacts through time are recorded and entered in NETSIM as series of pretimed signal designations. There is no means of making controllers in NETSIM perform window stretching for LRT, but the pretimed plans contain the effects of this priority scheme. Thus, traffic in the model would respond to the same signals that are encountered in the field, but LRVs would not influence controller behavior (and in fact, do not even need to be included in the simulation). If MOEs for partial priority schemes are required from the simulation, precise calibration is necessary to ensure that LRVs arrive at the necessary point in the phase to produce the arrival pattern being modeled.

STEP 6: Simulate Control and Placement Alternatives

The basis of comparison between alternative LRT system control types and geometric locations is the MOE information output by simulation and evaluation models. Though some decisions may be socially and/or politically driven and address concerns such as safety, environmental impact, land use, or fiscal planning, choices for operations and LRT system location are driven by maximizing system efficiency and transportation system benefits while minimizing LRT system cost and deleterious impacts on other modes of transportation.

Utilizing the recommended practice for each model, the analyst should be able to assemble the information required to compare the impacts, identified through MOEs such as delay and queue length, of various control priority schemes for LRT and geometric placement impacts. Analysts should exercise caution to ensure that comparisons are made with similar descriptive data. For instance, the analyst should not weigh the results from one model against the results of another model simulating two different alternatives. Differences could be due to the difference in the models as well as the differences in the two cases being analyzed. Also, the analyst should not compare an evaluation of existing conditions without LRT with optimized plans that include LRT. Differences are attributable to both the presence of the LRT control scheme and the optimization itself. It is recommended that the analyst optimize existing conditions (pre-LRT), and compare those results with LRT scenarios.

Monitoring data compatibility between models is also necessary. Some models, such as the HCS, output stopped delay while most of the others output total approach delay. Similarly, the analyst should check queue length output to see if the output is average queue length or maximum queue length. Checks of this type are important for data consistency and data report reliability.

STEP 7: Check for System Failures

Analysts should perform primary checks on the model output to identify locations, if any, where queue lengths are excessive, where demand exceeds capacity (i.e., delays are unusually high), and where the output does not agree with the analyst's knowledge of the field conditions or intersection operations that are being modeled. Essentially, these are checks for reasonableness and checks for problem locations in the network. Secondary checks of the model's presentation of graphical output (if present) can help identify these problem locations and confirm that the model is performing a realistic simulation or evaluation.

Queue Length

Queue length problems can be identified at locations where queues are sufficiently long to spill back into an upstream intersection (especially where storage distance is limited along short block lengths), block access to right and/or left-turn bays, or block major access driveways. Some models output queue length in number of vehicles, so these outputs must be manually converted to queue distance. A commonly used multiplier for the vehicle length conversion is 7.6 meters (25 feet), but this number may need to be modified if longer vehicles (trucks or buses) are present in the vehicle stream in considerable numbers. It must also be determined if the appropriate queue length for this check is the average queue length or the maximum queue length. In both cases, some averaging is already present in most model applications since input volumes are average hourly traffic volumes. Average queue lengths, computed as the average number of vehicles per lane that arrive on red multiplied by the red time, can be converted to various estimates of percentile queues using multipliers validated by Berry (*22*):

1.0 for average queue length,
1.5 for 85th percentile queue length, and
2.0 for 95th percentile queue length.

Higher percentile multipliers, which produce longer estimates of queue length, are applied where traffic flows are variable and where the impacts of queue spillback jeopardize operations and safety, such as potential spillback into an upstream intersection. The analyst determines the portion of the queue length that can be attributed to the introduction of LRT into the system by comparing the model outputs from the control case (no LRT) to the outputs including LRT. In cases where alternatives that both include LRT are compared, the difference in queuing between the assessment of existing conditions and the alternative indicates queuing caused by the alternative implementation.

Person Delay and Vehicular Delay

Analysis checks using delay are more difficult to define than those based on queue length. First, analysts must determined whether vehicular delay or person-delay is appropriate for the analysis at hand. Vehicular delay is computed on a per vehicle basis, regardless of whether the vehicle carries 1 or 80 passengers. Person-delay is computed as the average delay per person commuting through the intersection. Model outputs are virtually all based on vehicular delay, but the conversion to person-delay can be accomplished by multiplying the vehicular delay by the average ridership of the vehicle. Automobile ridership often ranges from 1.1 to 1.2 persons per vehicle, and LRV ridership often ranges between 50 to 80 persons per vehicle during the peak periods and 15 to 40 persons per vehicle during the off-peak periods (though the capacity of modern LRVs is as high as 75 seated passengers and 180 total passengers).

Delay outputs from the models can be in the form of stopped delay, approach delay, or both. Stopped delay defines the average time that vehicles are stopped at the intersection, while approach delay is the time during which vehicles approaching the intersections are not moving at free flow speed. The Highway Capacity Software, for one, outputs average stopped delay, while most other models produce average approach delay. The conversion to approach delay is made by multiplying stopped delay by 1.3 (*23*). Conversely, approach delay is converted to stopped delay by dividing by 1.3. The HCM (*5*) level-of-service criteria for stopped delay at signalized intersections are shown in Table 8. In addition to providing an idea of how average stopped delay relates to the quality of intersection performance, Table 8 also identifies approximately one minute of delay as an upper limit of "reasonable" delay.

Table 8. Level-of-Service Criteria for Signalized Intersections (*5*)

Level-of-Service	Stopped Delay (seconds per vehicle)
A	≤ 5.0
B	5.1 to 15.0
C	15.1 to 25.0
D	25.1 to 40.0
E	40.1 to 60.0
F	> 60.0

Given the above criteria for queue length and delay, analysts must check the model outputs for all approaches to all intersections for queuing problems or delay problems. If such problems are encountered, the analyst should first check the input code for errors. If no errors are present, the problems identified by queues or excessive delay point to potential system failures and intersection operations that may require reallocation of green time, redesign of intersection geometry (including turn bay redesign and driveway relocation), or, simply, an infeasible alternative for operation as an at grade LRT crossing. The Institute of Transportation Engineers (*17*) has published LRT grade separation guidelines, and Table 9 summarizes a screening for LRT crossings that should be considered for grade separation, partial or no LRT priority, and candidates for LRT preemption.

Table 9. LRT Crossing Alternatives Criteria (derived from *17*)

Crossing ADT	Category (for LRT headways > 6 minutes*)
< 20,000	A, At grade operation is feasible under most circumstances
between 20,000 and 40,000	B, Site specific conditions are critical and traffic control schemes, rather than preemption, are possible if some LRT delay is acceptable
> 40,000	C, At grade operation with full preemption is likely to cause significant intersection operational problems
> 55,000	D, At grade operation is not likely to be feasible under even the more restrictive LRT grade crossing solutions

* With more frequent LRT service, up to three minutes, these thresholds are 15,000; 30,000; and 50,000 ADT

STEP 8: Compute User Costs and Select Preferred Alternative

Once the simulation and/or evaluation results are output, checked, interpreted, and recorded, they are converted to motorist and transit user costs to determine the absolute costs for LRT implementation. The same data must be generated for all alternatives to provide a uniform base of comparison. It is important that the analyst use the same program for the control case and for all of the alternatives analyzed. That is, if NETSIM is used to model existing conditions, NETSIM should also be used for the alternatives analysis and output should only be compared with other NETSIM outputs.

Combinations of control case (existing conditions) and alternative studies determine the impacts of LRT implementation alternatives. The differences in MOEs between each alternative and the control case are the impacts attributable to the alternative, and the analyst assigns user costs based on the MOE quantities. For delay impacts (in units of delay per person), the difference in delay is multiplied by the number of hours per day the alternative plan is in operation to compute the daily difference in delay. A nominal 300 days per year are multiplied by the daily delay to produce annual delay difference in hours per person. Finally, this product is multiplied by the cost per hour of delay, typically eight to ten dollars per hour. Costs can be assigned to other MOEs, such as stops, fuel consumption, and emissions, if this type of output is available from the model selected for the analysis.

4.0 CONCLUSION

This report contains a step-by-step procedure for analyzing LRT at grade impacts at isolated crossings, crossings found along arterial streets, and crossings within signalized networks. Based on familiarity with the environment in which the LRT system is or will be implemented and the type of crossings found in this environment, the analyst selects software appropriate for the conditions at hand. The more complex arrangments of geometry and interconnected signal systems require more complex models to account for the variables affecting traffic behavior; however, more complex models also tend to require more input data and more coding effort than simpler models. Once the appropriate model is selected, the analyst uses data collected from the system - or projected values if the system does not yet exist - as input, codes and calibrates the model to existing conditions or default values found in this report, and performs the LRT and traffic system modeling. If system checks reveal no system failures, such as queue spillback or excessive delay, the results are converted to system user costs and the best alternative is chosen for implementation.

The primary benefit of this procedure is that it presents a standard methodology for evaluating the operations of LRT crossings. Analysts can compare alternative designs or alternative operating strategies objectively for their traffic and rail transit impacts, and a common set of performance measures can be generated and used to select the optimum alternative. With a proven methodology, such as the one contained in this report, a uniform base of comparison is established to assess the impacts of LRT operations. Ultimately, the analyst will be able to perform a comprehensive assessment of realistic LRT alternatives and traffic impact mitigation strategies and determine an optimum solution.

5.0 REFERENCES

1. C. H. Walters, S. P. Venglar, D. B. Fambro, and J. R. Daniel. *Development of Analytical Tools for Evaluating Operations of Light-Rail At-Grade Within an Urban Signal System - Interim Report,* Research Report 1278-1. Texas Transportation Institute, Texas A&M University System, College Station, TX, 1993.

2. S. P. Venglar, D. B. Fambro, and C. H. Walters. *Development of Analytical Tools for Evaluating Operations of Light-Rail At-Grade Within an Urban Signal System - Interim Report 2,* Research Report 1278-2. Texas Transportation Institute, Texas A&M University System, College Station, TX, 1994.

3. John F. Hickman & Associates. *Development of Analytical Tools for Evaluating Operations of Light-Rail At-Grade Within an Urban Signal System - Interim Report 3*, Research Report 1278-3. Texas Transportation Institute, Texas A&M University System, College Station, TX, 1994.

4. M. Bates and L. Lee. At-Grade or Not At-Grade: The Early Traffic Question in Light Rail Transit Route Planning. In *Light Rail Transit: New System Successes at Affordable Prices, TRB Special Report 221*, Transportation Research Board, National Research Council, Washington, D. C., 1982, pp. 351-367.

5. *Special Report 209: Highway Capacity Manual.* Transportation Research Board, National Research Council, Washington, D. C., 1985.

6. *Highway Capacity Software User's Manual.* U.S. Department of Transportation, Federal Highway Administration, Office of Traffic Operations, Washington, D. C., 1987.

7. E. C. P. Chang and C. J. Messer. *Arterial Signal Timing Optimization Using PASSER II-90*, Research Report 467-2F. Texas Transportation Institute, Texas A&M University System, College Station, TX, 1991.

8. C. E. Lee, R. B. Machemehl, and W. M. Sanders. *TEXAS Model Version 3.0 (Diamond Interchanges)*, Research Report 443-1F. Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin, Austin, TX, 1989.

9. *EzVIPAS 1.0 User Guide*. VIGGEN Corporation, 1993.

10. N. A. Chaudhary and C. J. Messer. *PASSER IV - 94 Version 1.0 User/Reference Manual,* Research Report 1271-1F. Texas Transportation Institute, Texas A&M University System, College Station, TX, 1993.

11. K. G. Courage and C. E. Wallace. *The MOST Reference Manual, Volume 4 TRANSYT-7F User's Guide*. U. S. Department of Transportation, Federal Highway Administration, Office of Traffic Operations and Intelligent Vehicle/Highway Systems, Washington, D. C., 1991.

12. *TransSim II™ Data Input Instructions.* JRH Transportation Engineering, Eugene, OR, 1993.

13. *TRAF User Reference Guide*, Publication No. FHWA-OR-92-060. Federal Highway Administration, Office of Safety and Traffic Operations Research and Development, U.S. Department of Transportation, McLean, VA, May, 1992.

14. B. Rymer, J. C. Cline, and T. Urbanik. *Delay at Isolated Light Rail Transit Grade Crossings.* Texas Transportation Institute Report 339-10, Texas State Department of Highways and Public Transportation, Austin, TX, 1987.

15. P. Luedtke, S. Smith, H. Lieu, and A. Kanaan. Simulating DART's North Central Light Rail Line Using TRAF-NETSIM. In *63rd Annual Meeting Compendium of Technical Papers*, Institute of Transportation Engineers, Washington, D. C., September, 1993, pp. 60-64.

16. R. A. Berry. Estimating Level of Service of Streets with At-Grade Light Rail Crossings. In *ITE 1987 Compendium of Technical Papers*, Institute of Transportation Engineers, Washington, D. C., August 1987, pp. 167-172.

17. ITE Committee 6A-42. *LRT Grade Separational Guidelines.* Institute of Transportation Engineers, Washington, D. C., 1990.

18. T. A. Ryan. Roadway Vehicle Delay Costs at Rail-Highway Grade Crossings. In *Transportation Research Record 1262*, Transportation Research Board, National Research Council, Washington, D. C., 1990, pp. 31-38.

19. *Manual on Uniform Traffic Control Devices.* U. S. Department ofTransportation, Federal Highway Administration, Washington, D. C., 1988.

20. F. J. McGinley. Active Tram Priority in Co-ordinated Signal Systems. In *Australian Road Research*, September, 1983, pp. 173-184.

21. P. S. Marshall and W. D. Berg. Evaluation of Railroad Preemption Capabilities of Traffic Signal Controllers. In *Transportation Research Record 1254*, Transportation Research Board, National Research Council, Washington, D. C., 1989, pp. 44-49.

22. R. Berry. *A Method to Estimate the Traffic Impacts of At-Grade Light Rail Crossings.* Master Thesis, University of Texas at Arlington, 1990.

23. W. R. Reilly and C. C. Gerdner. Technique for Measuring Delay at Intersections. In *Transportation Research Record 644*, Transportation Research Board, National Research Council, Washington, D.C., 1977, pp.1-7.

APPENDIX A

EXAMPLE DATA SHEET

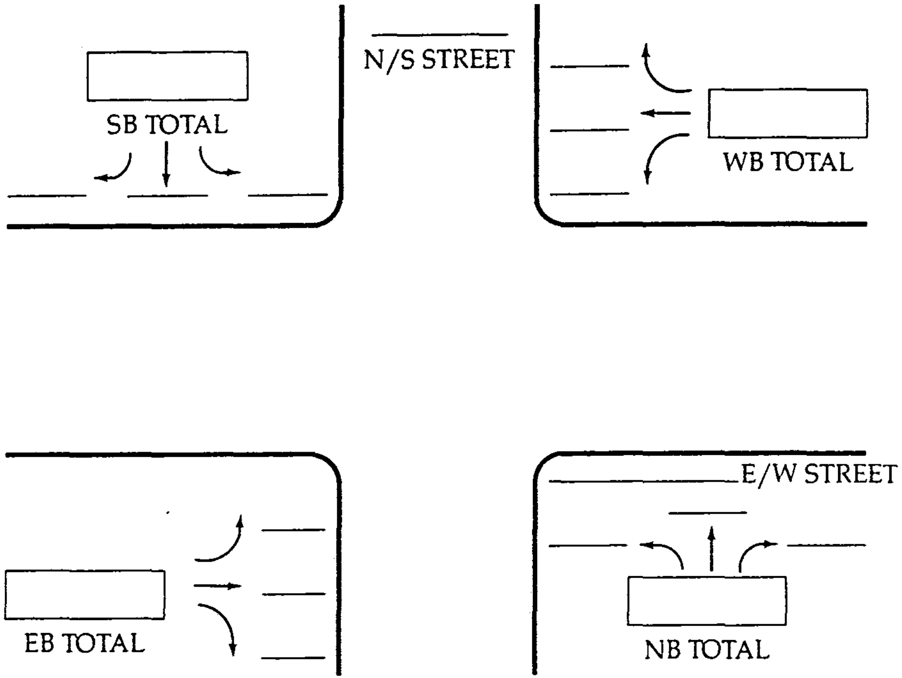
INPUT WORKSHEET

Intersection: ____________________ Date: ____________

Analyst: ____________ Time Period Analyzed: ____________ Area Type: ☐ CBD ☐ Other

Project No.: ____________ City/State: ____________

VOLUME AND GEOMETRICS



IDENTIFY IN DIAGRAM:

1. Volumes
2. Lanes, lane widths
3. Movements by lane
4. Parking (PKG) locations
5. Bay storage lengths
6. Islands (physical or painted)
7. Bus stops

TRAFFIC AND ROADWAY CONDITIONS

Approach	Grade (%)	% HV	Adj. Pkg. Lane		Buses (N_B)	PHF	Conf. Peds. (peds./hr)	Pedestrian Button		Arr. Type
			Y or N	N_m				Y or N	Min. Timing	
EB										
WB										
NB										
SB										

Grade: + up, − down
HV: veh. with more than 4 wheels
N_m: pkg. maneuvers/hr

N_B: buses stopping/hr
PHF: peak-hour factor
Conf. Peds: Conflicting peds./hr

Min. Timing: min. green for pedestrian crossing
Arr. Type: Type 1-5

PHASING

DIAGRAM								
Timing	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =
Pretimed or Actuated								

↗ Protected turns	- - ↗ Permitted turns	------- Pedestrian	Cycle Length ______ Sec

APPENDIX B

ALTERNATIVE ANALYSIS TOOLS

Traffic and Rail vehicles General Microscopic Simulation Model (TRGMSM)

TRGMSM was developed by Wu and McDonald of the Transportation Research Group at the University of Southampton, UK. TRGMSM simulates road vehicle movements at an isolated intersection, including buses and fixed lane/route transit vehicles, and light rail transit. Intersections within the model can have three or four approaches and a maximum of four lanes (not including LRT tracks), and alternative LRT station locations can be analyzed. The analyst can simulate fixed time or traffic actuated traffic signals and various types of priority. Total person delay and average vehicle delay are used as the main assessment factors for the simulation results analysis, based on a vehicle occupancy of 1.5 persons per vehicle and LRT occupancy of 80 passengers per vehicle (*1*).

Conclusions for engineers and LRT planners reached based on analysis runs performed using TRGMSM include the following (*2*):

1. Increasing LRT frequencies does not necessarily cause significant vehicle delay and person delay. In the studied situation, the LRT with actuated, LRT full priority control did not cause significant extra vehicle and person delay as LRT frequency varied from 2 to 40 vehicles per hour.
2. Different LRT station positions make differences in delays, particularly the person delay.
3. Among all the control measures, actuated, LRT full priority control produced the minimum person delay without causing significant extra vehicle delay. The actuated, railroad preemption control, though producing similar person delay to actuated, LRT full priority control, resulted in maximum vehicle delay.
4. Giving LRT high priority and using mid-block LRT station locations can significantly reduce intersection total person delay.
5. Apart from the safety consideration, restricting or reducing the left-turn traffic in the main street decreases vehicle and person delays in the intersection.

References:

1. J. Wu and M. McDonald. *Tram Delays at Traffic Signaled Intersections*. Paper prepared for the 1993 Light Rail Conference, International Convention Centre, Birmingham, UK, 1993.

2. J. Wu and M. McDonald. The Effects of At-Grade LRT at Signalized Intersections. In *ITE 1994 Compendium of Technical Papers*, Institute of Transportation Engineers, Washington, D. C., September, 1994, pp. 481-485.

VISSIM/VISSIG

PTV Vision is a suite of software with applications in transportation planning and traffic management. The software was developed by PTV-GROUP, Karlsruhe, Germany. VISSIM, one of the traffic management programs included in the suite, is a tool for the design of traffic actuated control systems involving public transport priority measures. Intersection and transit station details can be modeled, and the vehicular treatment in the model is stochastic and microscopic. The traffic model within the program suite uses car following logic and even employs such advanced features as lane changing. Using the simulator, the effects of different control strategies and signal patterns can be analyzed using such MOEs as travel times, queue lengths, and delays. VISSIG, which functions with VISSIM, is used for the computation of intergreen arrival times, optimization of fixed time signal plans, co-ordination of signal plans, data management, and graphical presentation.

Distribution: PTV Vision is produced by and made available through:

PTV System
Pforzheimer Str. 15
D-76227 Karlsruhe
Germany.