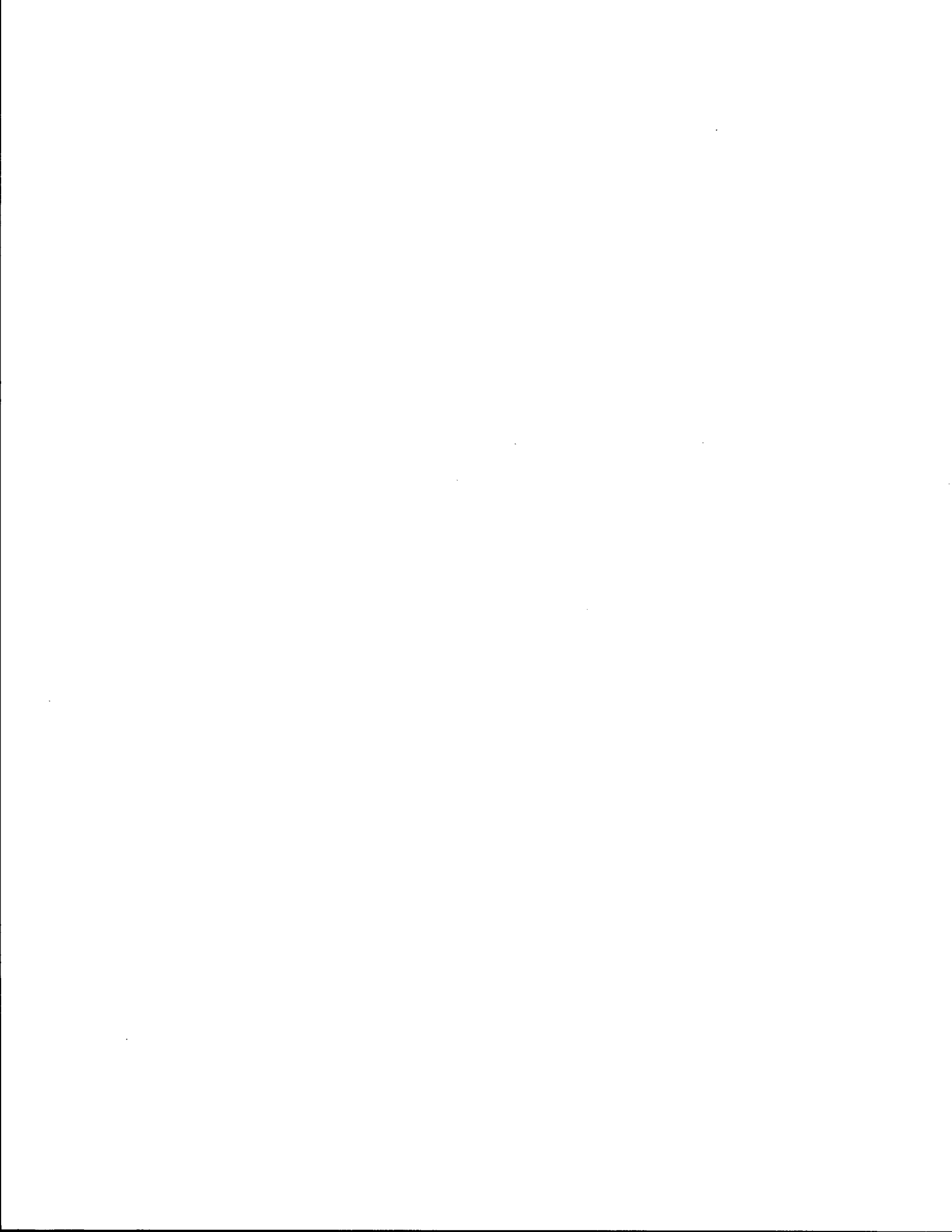


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16. Abstract This report identifies and recommends measures of impact that are applicable to the operation of at-grade light rail crossings within traffic signal systems. The key point in identifying measures of impact is to maintain consistency with traffic signal measures of impacts. The recommended measures of impact include average delay and queue length. This report illustrates how the analyst can apply both manual calculation methods and computer models to estimate these measures of impact. Included in the discussion is a screening procedure that is designed to minimize total work effort by identifying impacts and mitigating them with the least intensive analysis method. However, if the analysis results are marginal, then full simulation of the traffic signal system including the light rail line is warranted. The recommended programs for such evaluation are TRANSYT-7F for simpler problems and Traf-NETSIM for complex problems and analysis of system variances.					
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**DEVELOPMENT OF ANALYTICAL TOOLS FOR
EVALUATING OPERATIONS OF LIGHT RAIL
AT-GRADE WITHIN AN URBAN SIGNAL SYSTEM:
INTERIM REPORT 3**

by

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IMPLEMENTATION STATEMENT

The following report is the third interim report for project 1278. This report discusses various measures of impact used to estimate the effect of at-grade light rail operations on traffic signal systems. Recommendations are made on the most suitable measures of impact, and methods of estimating these measures using manual calculation and computer-based traffic signal evaluation models are presented.

The completed research, of which this interim report forms a part, will provide engineers with a method and computerized procedure for assessing the effects of a light rail system on a signalized urban arterial street network. Through analyzing various configurations of roadway and track geometry and signalization alternatives, the engineer can make decisions for the optimum light rail guideway placement and traffic signal operations in an efficient and organized manner.



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 this project were Carol H. Walters, P.E. #51154 (Texas), Daniel B. Fambro, P.E. #47535 (Texas) and Richard A. Berry, P.E. #57161 (Texas).

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TABLE OF CONTENTS

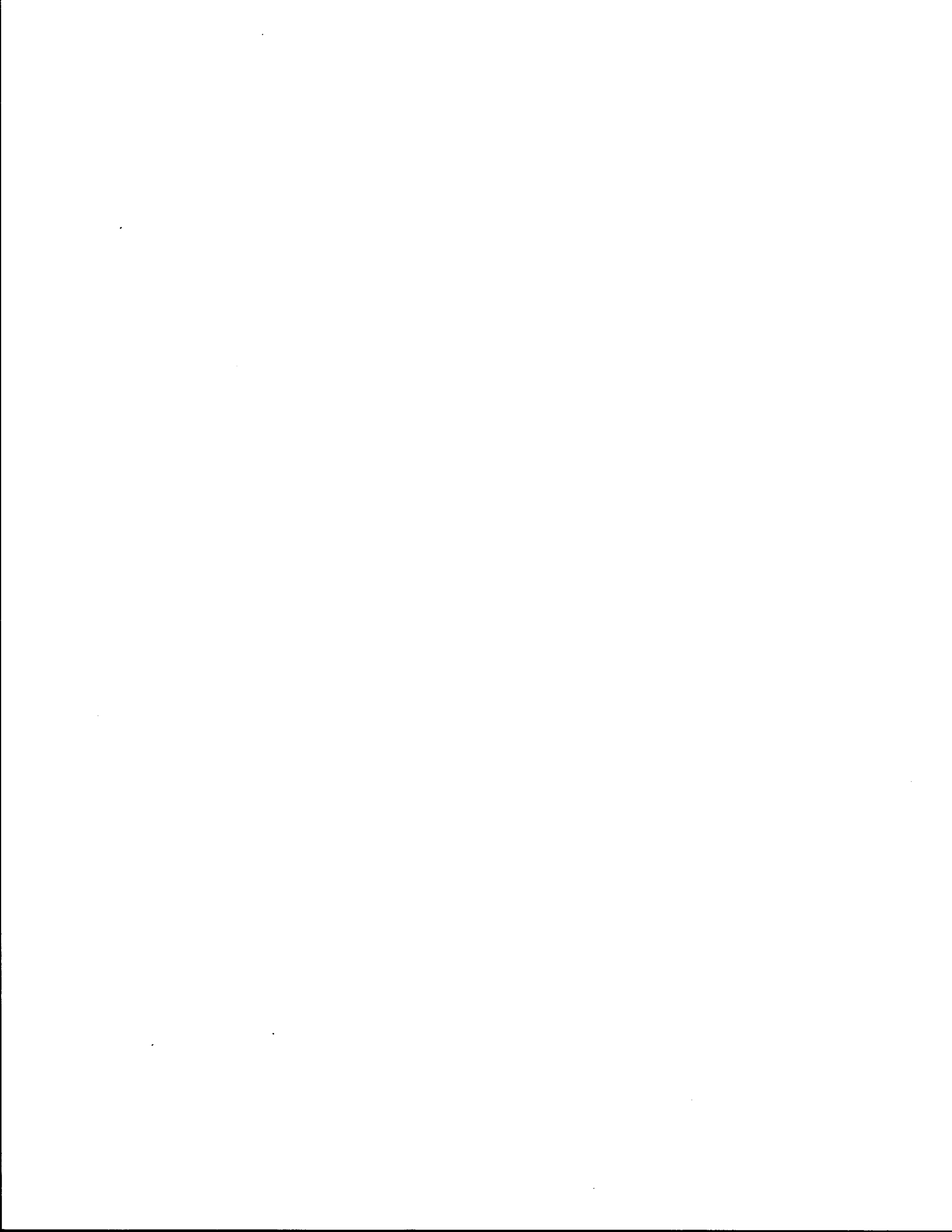
LIST OF TABLES	xi
SUMMARY	xiii
1.0 INTRODUCTION	1
1.1 BACKGROUND	1
1.2 PURPOSE	1
1.3 LAYOUT OF THE REPORT	2
2.0 SELECTING MEASURES OF TRAFFIC AND LIGHT RAIL IMPACTS ..	3
2.1 BACKGROUND	3
2.2 CANDIDATE MEASURES OF IMPACT	4
2.3 OTHER APPLICATIONS	6
2.4 APPLICATION OF MEASURES OF IMPACT	8
2.4.1 Load Factor	8
2.4.2 Delay	9
2.4.3 Travel Speed	11
2.4.4 Queuing Distance	13
2.4.5 Recommendations	18
3.0 OVERVIEW OF MODELS AND METHODS	19
3.1 KEEP IT SIMPLE STUPID	19
3.2 TYPES OF CROSSINGS	19
3.3 TYPES OF METHODS	20
3.4 USEFUL MANUAL CALCULATION TECHNIQUES	20
3.5 COMMONLY USED COMPUTER MODELS	21
3.6 RECOMMENDED SCREENING PROCEDURE	21

TABLE OF CONTENTS (continued)

4.0	TYPICAL APPLICATION OF MODELS TO PROBLEMS	41
4.1	INTRODUCTION	41
4.2	HIGHWAY CAPACITY SOFTWARE	41
4.3	PASSER II	42
4.4	PASSER III	45
4.5	TRANSYT-7F	46
4.6	TRAF-NETSIM	50
5.0	SUMMARY AND RECOMMENDATIONS	53
6.0	REFERENCES	55
7.0	APPENDIX	57

LIST OF TABLES

1	Example Travel Speed Calculations	12
2	Typical Light Rail Vehicle Characteristics	25
3	Example Train Time-distance Trajectory, Travel from Station A to D	26
4	Example Train Time-distance Trajectory, Travel from Station D to A	27
5	Mean Standard Deviations for Headways at Crossings	28



SUMMARY

The purpose of this report is to summarize the means and methods of analysis of the impacts of at-grade light rail transit on traffic operations -- especially within traffic signal system environments. Rail transit has a significant impact on traffic operations on streets and highways. The degree of impact varies depending on the degree of interface between the rail and highway modes of travel. In-street rail operations will have greater impacts than light rail on exclusive rights-of-way where all crossings are either mid-block at-grade or grade separated. This report identifies and recommends measures of impact (average delay and length of queue assuming an nth percentile vehicle arrival rate) that are applicable to the operation of at-grade light rail crossings within traffic signal systems. The key point in identifying measures of impact was to maintain consistency with traffic signal measures of impacts.

The analyst can apply both manual calculation methods and computer models to estimate these measures of impact. A screening procedure designed to minimize total work effort identifies impacts and mitigates them with the least intensive analysis method. The Highway Capacity Software can be applied to all types of at-grade light rail crossings, so long as each crossing is considered on an individual basis, and is the simplest analysis tool after manual calculation techniques. PASSER II follows the Highway Capacity Software as the next simplest analysis tool and can be applied to all types of at-grade light rail crossings. The arterial evaluation capabilities of PASSER II are one of the primary strengths of this program. PASSER III is nearly perfectly designed to analyze median-running light rail within an arterial traffic signal system. However, if the analysis results are marginal, then full simulation of the traffic signal system including the light rail line is warranted. The recommended programs for such evaluation are Traf-NETSIM for complex problems and analysis of system variances and TRANSYT-7F for simpler problems.



1.0 INTRODUCTION

1.1 BACKGROUND

During the late 1970's and throughout the 1980's to the present, metropolitan areas in Texas have been moving toward implementation of light rail transit as an alternative to bus transit and travel by private automobile. One of the reasons transit agencies are including light rail in their plans is that it is less costly to build and operate than heavy rail options while it provides the "glamour" of rail transit that is necessary to sell voters on local option sales tax increases that will fund all modes of transit.

For most of the twentieth century, rail transit in the form of trolleys, street railways, and interurbans were fixtures in major Texas cities. However, during the post-World War II years, changes in urban land use patterns and densities coupled with widespread private automobile ownership and the development of the modern highway system left rail transit without a market share large enough to survive on.

In the forty years since rail transit was a common fixture in major Texas cities, motorists have lost the knowledge and driver expectancy of how to coexist with rail transit in an urban environment. In the coming years as rail transit returns to Texas, motorists will be relearning to watch for rail transit while they drive. Meanwhile, rail transit options -- primarily light rail -- will have a significant impact on traffic operations on streets and highways. The degree of impact will vary depending on the degree of interface between the rail and highway modes of travel. In-street rail operations will have greater impacts than light rail on exclusive rights-of-way where all crossings are either mid-block at-grade or grade separated.

1.2 PURPOSE

The purpose of this report is to summarize the means and methods of analysis of the impacts of at-grade light rail transit on traffic operations -- especially within traffic signal system environments. The primary means and methods are applied by the general traffic engineering practitioner without a specific background in advanced computer simulation. The results these means and methods provided vary depending on the level of analysis from general order-of-magnitude results to finely detailed estimates of impacts.

1.3 LAYOUT OF THE REPORT

This report is composed of four sections: an introduction, a discussion on the selection of measures of traffic and light rail impacts, a discussion of models and methods, and lastly, some typical applications of some of the models.

2.0 SELECTING MEASURES OF TRAFFIC AND LIGHT RAIL IMPACTS

2.1 BACKGROUND

As defined by the Highway Capacity Manual (1), streets that have at-grade light rail grade crossings are, for the purposes of level of service analysis, interrupted flow facilities. According to the Manual, interrupted flow facilities have fixed elements that cause periodic interruptions to traffic flow, and such elements include traffic signals, stop signs, and other types of controls. Further, the Manual states that these devices cause traffic flow to periodically stop irrespective of how much traffic exists.

It is reasonable then that the measures of traffic and light rail impact should be consistent with those for interrupted flow facilities. These measures include, specifically, motor vehicle delay and travel speed. Other measures have, however, been used by some analysts such as load factor and queue lengths, and still other analysts have tried to apply benefit - cost analysis and cost effectiveness measures. All of these approaches can be applied, although some are of more value than others when explaining the effect of light rail operations on a traffic signal system.

When identifying and classifying candidate measures of traffic and light rail impact, it must be remembered that the user may not be familiar with the nuances of the measure of impact used. In the following paragraphs, candidate measures of impact are identified. Application of each of these measures has been attempted at one time or another by engineers and planners working for transit agencies actively engaged in light rail development.

Not all of the measures of impact have proved practical or, indeed, desirable within the political arena where the ultimate decisions are made. Some measures of impact give results that are vastly different from other measures of impact and, as a result, confuse the decision-making process. Our recommendations, therefore, consider the global implications of a measure of impact -- not just the ease with which it can be estimated.

2.2 CANDIDATE MEASURES OF IMPACT

The following four candidate measures of impact have been identified from a review of the literature on light rail operations and from discussions with consultants actively engaged in the analysis of the traffic impacts of at-grade light rail crossings:

- o Load factor,
- o Delay,
- o Travel speed,
- o Queue length, and
- o Other applications.

Load factor is defined in the second edition of the Highway Capacity Manual (2) as the ratio of fully loaded traffic signal cycles on a given intersection approach to the total number of traffic signal cycles on that intersection approach in the time period. A fully loaded traffic signal cycle on an intersection approach is one in which not all of the vehicles in the queue at the beginning of the green phase clear the intersection before the end of the green phase. In simpler terms, some vehicles on the intersection approach must wait through more than one red phase before clearing the intersection. Levels of service from "A" through "E" were defined in the Manual for various load factor ratios. Today, load factor is a somewhat archaic measure of impact, although it has been used by at least two transit agencies (San Diego (3) and Dallas (4)) in the past as part of their analysis method.

Delay is defined in the third edition of the Highway Capacity Manual (1) in two forms -- as stopped delay and as approach delay. Either measure can be used for level of service determination, although stopped delay is easier to measure in the field. Stopped delay is defined as the time during which vehicles in a lane group on an intersection approach are not moving. It can be computed on a "total" basis as the summation of the discrete stopped delays of each vehicle in the lane group moving through the intersection during the time period or on an average "per vehicle" basis where the total stopped delay for all of the vehicles in the lane group is divided by the total number of vehicles in the lane group moving through the intersection during the time period. Levels of service from "A" through "F" are only defined for various amounts of average individual stopped delay, although it is an easy calculation to convert them to approach delay

values. Delay is probably the most widely used measure of impact for interrupted flow facilities at this time.

Approach delay is defined as the time during which vehicles in a lane group on an intersection approach are not moving at their free speed. It includes stopped and moving delays. Moving delays occur during acceleration and deceleration when a vehicle transitions from a stopped condition to free-flow operation. Like stopped delay, approach delay can be computed on a "total" basis or on an average individual basis. Levels of service are not defined by the Highway Capacity Manual (1) for approach delays.

Research into the relationship between stopped delay and approach delay has resulted in a recommended ratio of 1.3 (1). Average approach delay is approximately 30 percent greater than average stopped delay. Average approach delay is an output of three computer models that can be applied to at-grade light rail crossings within traffic signal systems.

Travel speed is defined in the third edition of the Highway Capacity Manual (1) as the average speed at which vehicles can traverse a section of roadway. Levels of service from "A" through "F" are defined for various combinations of roadway types, characteristics, and travel speeds. Travel speed can be estimated by dividing the travel distance by the sum of the total of the average individual approach delays and the inter-intersection travel times.

Queuing distance on an intersection approach can be defined in two ways. First, it can be defined by the number of stopped vehicles in a lane group or on an intersection approach that arrive during the red phase. This distance we define as "back of queue at end of red." Second, it can be defined as "maximum back of queue." Maximum back of queue includes not only the vehicles that arrive and stop during the red phase, but also those vehicles that arrive and stop during the discharge of the leading vehicles in the queue. Neither the "back of queue on end of red" distance nor the "maximum back of queue" distance may contain the actual maximum queue length. However these two measures do define important points in queue formation and discharge that can affect traffic operations at other nearby roadway features, such as driveways, lane drops, and intersections.

2.3 OTHER APPLICATIONS

In addition to the foregoing candidate measures of impact, there have been other measures considered including:

- o Benefit-cost methods,
- o Accident prediction formulae and priority indices, and
- o Railroad grade-separation warrant criteria.

Benefit-cost methods and the closely associated cost effectiveness indices can provide an overall view of various capital outlay options such as comparing a street closure versus an at-grade crossing versus a grade separation. However, application of benefit-cost methods requires extreme judgement by the analyst and is highly subject to the political process. The primary reasons can be found by reviewing the basic outline of the method.

Physical, operational, and sometimes institutional data are estimated that describe the various options to be evaluated. Monetary values are placed on each of these inputs. A life span for each system is estimated and a capital recovery factor is estimated, and the benefits of each are compared to the costs of each, resulting in a descriptive ratio. The problem is that so many of these factors are estimates based on estimates that accuracy is lost. Among the components of the benefit-cost method that may be most prone to debate are the value of time and the capital recovery factor.

Dallas Area Rapid Transit (DART) tried to use benefit-cost as a measure of impact during 1987 and 1988. The primary problems that DART consultants (including one of the authors of this report) faced were related to the value of time and the capital recovery factor. At that time, the Urban Mass Transit Administration (UMTA) specified a value of time in the range of \$2.00 to \$4.00 per hour for travel cost depending on the trip type. At the same time the Texas Transportation Institute (TTI) recommended a value of \$8.40 per hour for travel time, and the North Central Texas Council of Governments (NCTCOG) recommended the use of \$10.00 per hour for travel time. Because Federal funds were expected to be involved, DART chose to use the UMTA cost figures so that consistency would be maintained when calculating required cost effectiveness indices. The Texas Department of Transportation (TxDOT) contended that the UMTA costs were too low and that TTI's cost estimate should be used. Other groups contended that the NCTCOG costs should be used. Much debate was expended on this item. It was likewise

with the capital recovery factor. DART's financial personnel figured the cost of money to DART at that time to be in the 3 to 4 percent per year range. DART's consultants and others figured that the cost of money should have been near the market rate of the time -- 10 percent, or so. The vast differences between these two sets of values, travel costs and capital recovery factors, were easily shown to swing decisions from a point of constructing at-grade crossings to a point of constructing grade separations although the traffic and light rail volumes remained the same for both cases. Based on these shortcomings, our recommendation is to forego in-depth discussion of this class of analysis method. Transportation Research Record 1361 (4) provides a brief discussion of how the North Central Texas Council of Governments benefit-cost model (5) was used by DART.

Accident prediction formulae and priority indices, many of which can be found in the railroad-highway grade crossing literature, are not readily applicable to light rail operations for several reasons.

- o The purpose of the formula or index is to prioritize improvement and maintenance projects at highway-railroad crossings.
- o The formula or index is often estimating accidents.
- o The length of trains used to validate the formula or index is much greater than the typical length of a two, four, or six car light rail.
- o The number of trains per day used to validate the formula or index is much less than the number of light rail trains per day expected at a typical light rail crossing.
- o The traffic conditions used to validate the formula or index may be different from the urban environment in which light rail operates.
- o The formulae and indices provide a comparative base from which to make decisions in the railroad environment but do not assess the effect of rail operations on nearby highway features such as preempted signalized intersections.

Based on these reasons, our recommendation is to forego in-depth discussion of this class of analysis method.

Railroad grade-separation warrant criteria are also not readily applicable to light rail operations. The primary reasons include the following:

- o The assumption of long crossing blockage times such as those associated with freight train operations and

- o The weight given to trains per day that would discriminate against high volume light rail lines.

Based on these reasons, our recommendation is to forego in-depth discussion of this class of analysis method.

2.4 APPLICATION OF MEASURES OF IMPACT

2.4.1 Load Factor

There have been at least two instances where a load factor has been proposed or used to estimate traffic impacts of at-grade light rail crossings. One of these was a proposition by Stone and Wild (6) that used the work of May and Pratt and Crommelin to develop a regression equation relating the intersection utilization factor (ratio of volume to capacity) to individual vehicle delay. Because this method is based on the second edition of the Highway Capacity Manual (2), load factor is one of the primary parameters defining the capacity of an intersection approach. This method has been superseded by delay-based methods using the third edition of the Highway Capacity Manual (1).

In the second instance, the load factors at signalized intersections bounding a mid-block light rail crossing were used to estimate the maximum expected service volumes for each level of service on a scale of "A" through "F" (4). The maximum service volumes were further reduced by the percentages of time that the crossings were blocked. The resulting volumes were considered to set the level of service volumes for these mid-block crossings. This approach, developed by DART consultants in 1986, had merit before the wide distribution of the third edition of the Highway Capacity Manual (1). However, as an estimator of impacts, this method appeared to show potential level of service constraints at volume levels half as great as necessary to produce similar level of service constraints when methods based on average individual stopped delay were used. Transportation Research Record 1361 (4) provides an overview of this method.

Both load factor-based methods have been superseded by methods based on the level of service criteria used in the third edition of the Highway Capacity Manual (1). Consequently, we do not recommend continued consideration of this measure of impact.

2.4.2 Delay

Delay models have been successfully validated for at-grade light rail crossing applications for train headways exceeding 15 minutes. Berry (7) validated the basic delay equation in the Highway Capacity Manual (1) using pretimed control and random arrivals. It was the best among 20 delay models and model components that Berry studied. Berry (7) and Berry and Williams (8) provide an in-depth discussion of the other models and model components studied.

The application of the Highway Capacity Manual model is simple following two possible approaches. The simplest, but least accurate approach, is to estimate the average "traffic signal" cycle length based on the average number of trains during a time period. For example, if there are 24 trains per hour (12 in each direction, assuming two-way operation), then the cycle length is computed as follows:

$$3,600 \text{ seconds per hour} / 24 \text{ trains per hour} = 300 \text{ seconds per train.}$$

"Green" and "red" times are based on the crossing blockage time. Saturation flow is either measured in the field or estimated. The appropriate values are put in the equation, and the delay calculated for the at-grade crossing.

The second approach is similar, except that two calculations of cycle length are made -- one each for the time between consecutive trains, again, assuming two-way operation. It is not typical for the opposing trains to arrive at a crossing on equal intervals. Instead of being constant 300 second cycles, as assumed in the previous example, it is more likely that the cycle pattern may be something like 50 seconds and 250 seconds or 100 seconds and 200 seconds. For this approach, delay is calculated based on each portion of the cycle pattern, and the weight of these delays in the final estimate is proportioned according to the proportion of the traffic volume that arrives at the crossing during each part of the cycle pattern. Berry (7, 9) provides additional detail for estimating delay using this method.

The primary shortcoming to using delay as a measure of impact is deciding how to apply it equitably. The previous examples have been based solely on vehicular delays. The issues open to debate are listed below.

- o Should average vehicular delay be used or should it be person-delay?
- o If delay is to be minimized and person-delay is the measure, then should average person-delay at each individual crossing be minimized, accounting for rail and motor vehicle delays; or should person-delay of all crossings in a corridor be minimized? The issue here is best illustrated by example. Consider a light rail line that carries 7,500 persons per hour. This line crosses five streets, each of which carries 4,500 persons per hour. Should person-delay at each intersection be minimized based on a utilization proportion of 7,500 persons for light rail versus 4,500 persons for the cross-street, or should the person-delay of the corridor be minimized based on a utilization proportion of 7,500 persons for light rail versus 22,500 for the total cross-corridor person-trips on all five cross-streets?
- o Should delays to light rail operations such as those in the off-peak direction be considered when their purpose in the schedule is to mitigate possible deleterious at-grade crossing operations?

The issue of using vehicle delay versus person-delay is one of having good planning data from which to estimate vehicle occupancies for both motor vehicles and light rail. The primary problem during public debate is whether the vehicle occupancies and ridership numbers are accurate or (as usually thought of by the public) inflated. From the public perception standpoint, vehicle delay is a much simpler concept than person-delay, and one that is inherently less prone to manipulation. If ridership and vehicle occupancy numbers are known to be accurate, then it may be possible to use person-delay as a measure of impact.

Extending the foregoing argument over types of delay further, one can argue that the total delay to light rail ridership on a line during a time period should be balanced against delay to the persons traversing all of the at-grade crossings in that same corridor during that time period -- essentially minimizing the delay to all of the person-trips in a given corridor. However, this approach is not usually taken. The typical approach is to minimize the delay at individual at-grade crossings which results in the light rail ridership being given greater weight because instead of being counted in the analysis only once, the light rail ridership is counted repetitively at each individual at-grade crossing. Active discussion of this point should be encouraged at all levels within the transportation field.

The final point is that delays built into the light rail schedule to improve traffic operations should be considered when minimizing total person-delay. These hidden delays, typically in the off-peak direction of travel, are the result of not grade separating a crossing or preempting nearby traffic signals to give the light rail operation exclusive right-of-way through an at-grade crossing during all time periods.

2.4.3 Travel Speed

When a light rail line traverses a traffic signal system, it is not difficult to apply an average travel speed analysis using a variety of calculations, such as those described in the Highway Capacity Manual (1), or computer simulation routines, such as TRANSYT-7F or Traf-NETSIM. The basic technique consists of estimating the total travel time per vehicle on a section of the "base" street network and adding the additional average delay time at each at-grade crossing to the total travel time. Within the Highway Capacity Software package (10), the travel speed (urban and suburban arterials) level of service calculation includes a convenient input -- "other delay" -- where the grade crossing delay can be addressed simply and easily. The additional average delay time at each at-grade crossing will increase the network travel time and reduce the network travel speed, thus allowing for level of service comparisons using the level of service criteria for arterial streets in the Highway Capacity Manual (1).

Obviously, to apply a travel speed analysis, one must be able to estimate the delays incurred at each at-grade light rail crossing. This means that a level of service for the crossing itself is already available to the analyst through the application of the Highway Capacity Manual's interrupted flow levels of service.

While it would intuitively seem that travel speed would be a good measure of impact because it includes all delays that occur over a section of roadway, it is not in practice, because it is prone to subjective manipulation by the analyst. An examination of the debate that occurred in 1987 in Dallas, Texas, when DART consultants proposed travel speed provides a good case study.

At the time, the DART general engineering consultant was searching with DART staff for a method to determine the traffic impacts of at-grade light rail crossings that could be applied all across the proposed DART light rail system. Average travel speed, as the measure of impact for

arterial streets in the Highway Capacity Manual (1), seemed to be a good candidate. Using the methods for interrupted flow facilities, the consultants could estimate the approach delay at signalized intersections and at proposed at-grade crossings. The change in travel speed for a roadway segment between having an at-grade crossing and not having an at-grade crossing was considered representative of the impact of the at-grade crossing on traffic operations.

The problem that the consultants overlooked when conceptualizing the use of travel speed was travel speed's sensitivity to roadway segment length. For example, consider two roadway segments: one is 100 meters (328 feet) long and the other is 1,000 meters (3,280 feet) long. Assume that cross-sections and traffic volumes are identical for both roadway segments and that each includes an at-grade light rail crossing. Assume that the free speed on each street is 50 kilometers per hour (km/h) or approximately 30 miles per hour (mph) and that delays related to traffic signal operations at each end of each street segment amount to a total of 36 seconds of average approach delay. Finally, assume that the average approach delay related to light rail operations is 12 seconds for both roadways. Table 1 summarizes the travel speed calculations for each street segment.

Table 1. Example Travel Speed Calculations

	100 m (328 ft) street segment	1,000 m (3,280 ft) street segment
Intersection delay	36 sec.	36 sec.
Free speed travel time	7 sec.	72 sec.
Total travel time	43 sec.	108 sec.
Average travel speed	8.4 km/h (5.2 mph)	33 km/h (21 mph)
Grade crossing delay	12 sec.	12 sec.
Total travel time w/LRT	55 sec.	120 sec.
Average travel speed	6.6 km/h (4.1 mph)	30 km/h (19 mph)
Percent delay added by LRT	21 percent	9 percent

What is obvious when reviewing Table 1 is that although the delay related to light rail operations is identical for both roadways, the apparent impact of an at-grade light rail crossing on the 100 meter (328 foot) street segment is greater than the impact of the 1,000 meter (3,280 foot)

street segment. In terms of the raw change in speed, the delay associated with the at-grade light rail crossing did not affect the overall speed appreciably. In terms of percent change, however, the delay associated with the crossing was considerable.

At the most impacted point - the at-grade light rail crossing - the 12 seconds of approach delay would have resulted in a Level of Service "B" designation using an interrupted flow level of service while the travel speed levels of service would have been "F" for both cases for the 100 meter street segment, "A" for the 1,000 meter street segment without the crossing, and "B" for the 1,000 meter street segment with the at-grade crossing. When estimating average travel speed, the length of the roadway segment can be more important than the amount of delay incurred at an at-grade crossing.

2.4.4 Queuing Distance

Estimating the length of queues resulting from both traffic signal operations and at-grade light rail crossing blockages is not inherently difficult although this is an analysis type that requires good judgement to apply. The number of vehicles in the queue can be estimated using hand calculations, such as those described in many statistics textbooks, or computer simulation routines, such as TRANSYT-7F or Traf-NETSIM.

Before starting the analysis for either an intersection approach or an at-grade crossing approach, the analyst should be able to answer the following questions.

1. How sensitive is the end result to the degree of accuracy?
2. Should back of queue at end of red be used instead of maximum back of queue?
3. Can typical traffic flow distributions be estimated?
4. Is lane distribution equal or highly skewed?
5. Is there an upstream constraint that will control queue length by limiting the number of vehicles that pass that point?
6. What is the average length of vehicles within the queue? That is, what distance is assigned to each vehicle in the queue to convert from numbers of vehicles to distance?

The question on the degree of accuracy leads to a number of key decisions that include the following:

- o Choice of average queue length, 85th percentile queue length, 95th percentile queue length, 99th percentile queue length, etc. and
- o The calculation method that is applied.

The decision on the location of the end of the queue may be critical in some traffic signal system situations. If the at-grade crossings are far from signalized intersections and there are only driveways between the crossings and the signalized intersections, then back of queue at end of red may be appropriate because it describes that part of the queue that most significantly delays cross-traffic. On the other hand, if momentary intersection blockage cannot be tolerated, then maximum back of queue would be a better measure because it estimates where the last vehicle stops -- even if only momentarily.

The next question on traffic flow distributions defines more assumptions.

- o If the traffic flow is constant, then queue lengths are more stable from occurrence to occurrence, and an average queue length estimate may be adequate.
- o If traffic flow is highly variable, then a high percentile queue length may be needed to offset the variability, and estimation techniques that overestimate queue lengths may be more appropriate than techniques that underestimate queue lengths.
- o If the traffic flow distribution can be assumed to be stable over a period of years, then the distribution can be used to estimate the queue length at various percentiles.

The lane distribution question again defines a critical assumption.

- o If the number of vehicles in each lane is nearly equal, then queue length estimates can use standard Highway Capacity Manual equivalency factors.
- o If the number of vehicles in each lane is highly variable, then the analyst can make multiple queue length estimates on an approach so that the impact of the queue length for each lane can be individually assessed.

The question on upstream constraints addresses a condition many analysts overlook -- "What is the maximum number of vehicles that can physically arrive at the crossing or intersection approach while the crossing is blocked or the signal is red?" This simple question needs to be addressed because queue lengths are not infinite in length although that is what some calculations will tell us. If there is a constraint, such as a parking gate, toll booth, or an intersection approach

with a lot of "dead" green time that is not being used, then it should be included in estimating queue lengths.

The final question on vehicle length seems simple enough at first glance. It is, however, a question that can raise significant debate. The reason is that distance occupied by different vehicle classes and even different vehicles within a class varies considerably. It is one thing if all vehicles on a roadway facility are automobiles. Then 6.7 meters (22 feet) per vehicle may be adequate. It is something quite different if all of the vehicles on a roadway facility are 12.2 meter (40 foot) transit buses or tractors with 14.6 meter (48 foot) semi-trailers.

Among computer simulations that might be applied to the problem, TRANSYT-7F assumes a length of 7.62 meters (25 feet) per vehicle with no provision for increasing the queue length as the percentage of heavy vehicles increases. PASSER III uses number of vehicles that can be stored in a lane as an input and recommends 7.62 meters (25 feet) per vehicle. Traf-NETSIM provides intermediate output in terms of number of vehicles only, leaving the length calculation to the analyst. Among the hand calculations for queuing, all provide only a number of vehicles in the queue and leave the calculation of length as an additional step for the analyst.

After setting the assumptions, the next question answered concerns the technique used to estimate queue lengths. There are at least five variations on this theme.

1. Take the average number of vehicles per lane that arrive on red and multiply them by a factor:
 - 1.0 for average queue length,
 - 1.5 for 85th percentile queue length, and
 - 2.0 for 95th percentile queue length.

These factors taken from AASHTO (11) for left turn storage have been validated for light rail crossings by Berry (7) using 20 observation periods at 11 light rail grade crossings throughout the United States, both within and outside of traffic signal systems. They underestimate at low approach volume levels and overestimate at high approach volume levels. The resulting queue length estimate is for the number of vehicles in that lane at end of red.

To compute the maximum back of queue in the lane, the analyst must calculate the point of intersection between a line that describes the discharge rate of the queue and a line that describes the arrival rate of vehicles on the intersection approach. This point can be found with the following two equations:

$$t = (q(r) + 14.2(q) - 5)/(2.1 - q)$$

where

t = time to discharge the queue after saturation flow conditions have been reached,

q = vehicle arrival rate in vehicles per second (vps); $q < 2.1$ vps

r = red time or crossing blockage time, and

Q = $q(r + 14.2 + t)$ = maximum back of queue.

The derivation of these equations is given in the Appendix. These equations are based on Greenshield's queue discharge model (12) and are applicable for queues of at least five vehicles in length. For queues of less than five vehicles, the analyst can estimate the number of arrivals during the initial discharge and add that number to the initial discharge volume. For saturation flow rates that exceed 1,714 vehicles per hour green per lane (vphgpl), the analyst can reduce the saturation headway of 2.1 seconds per vehicle in the first equation to a level consistent with conditions in their area. Please note, however, that Berry (7) found saturation flows on at-grade light rail crossing approaches to be approximately 200 vphgpl less than saturation flows at nearby signalized intersections.

2. Use the traffic flow distribution and estimate the number of vehicles per lane that will arrive on red from the statistical distribution for each percentile in question. The resulting queue length estimate for that lane is for the number of vehicles at end of red. To compute the maximum back of queue in that lane, the analyst must calculate the point of intersection between a line that describes the discharge rate of the queue and a line that describes the arrival rate of vehicles on the intersection approach. The calculation is identical to that illustrated in the preceding paragraphs.

3. Use an accepted random arrival queuing formula such as the following:

$$Q = (\ln(0.5)/\ln(v/c)) - 1.0$$

where

$$Q = 95\text{th percentile queue length,}$$

$$v/c = \text{the ratio of volume to capacity, where volume is assumed the arrival rate and capacity is assumed the service rate, and}$$

$$\ln(x) = \text{natural logarithm of } (x).$$

This particular formula based on an M/M/1 queuing system (single channel, first-in, first-out, random arrival rate and random service rate system) is found in some traffic engineering textbooks and was derived from an exponential distribution. For the derivation, see Wohl and Martin (13). While some analysts may want to investigate it, it did fail validation testing by Berry (7) by consistently underestimating queue lengths measured in the field.

4. Use a computer program such as TRANSYT-7F that estimates the average maximum back of queue. The term "maximum back of queue" is somewhat misleading because the input for TRANSYT-7F uses average traffic volumes. To determine higher percentile maximum back of queue, the input volumes would have to be manipulated accordingly.
5. Use a computer program such as Traf-NETSIM that estimates the average queue length per lane on intersection approaches as part of its standard intermediate output. Although the queue length is an average, the microscopic nature of Traf-NETSIM allows the user to run the program with a variety of random number seeds so that multiple simulation runs can be aggregated together to statistically estimate higher percentile queue lengths from the intermediate output.

From a usefulness standpoint, the AASHTO method outlined above is an exceedingly easy method that usually gives conservative results and is sufficient for most early screening work during the light rail system planning process. The two computer programs are both useful with judgement applied. However, the TRANSYT-7F program is easier to code than Traf-NETSIM.

Either of these programs can be applied if more sophisticated analysis is needed. The estimates provided by any method should be checked for reasonableness and upstream constraint.

2.4.5 Recommendations

Based upon consistency with the Highway Capacity Manual (1) and previously validated measures, we recommend the following as a minimum set of measures of impact:

- o Motor vehicle delay and
- o Generated queue length, both from at-grade crossing operations and from nearby traffic signal operations.

Travel speed and benefit-cost applications are still possible, if necessary, with these two basic sets of impact criteria, leaving maximum flexibility available to the analyst while using a minimum of information.

3.0 OVERVIEW OF MODELS AND METHODS

3.1 KEEP IT SIMPLE STUPID

One of the primary shortcomings of most traffic engineering analysis methods is not identifying the primary user. Many methods are developed in the academic realm without sufficient consideration that the end user

- o May not be an engineer,
- o May not have had any continuing education,
- o May not have an advanced degree,
- o May not even have transportation as a specialty, and
- o May have to learn by doing.

This problem transcends agency barriers. It is conceivable on a light rail project that neither the consultants, municipal agencies, county agencies, State transportation agencies, nor transit authorities may have staff that can understand and apply a complex traffic engineering analysis. Therefore, in our discussions and proposals we have held that simplicity and straightforwardness are to be desired. While precision and accuracy do not have to be sacrificed to obtain simplicity and straightforwardness, the answers of any proposed method are but estimates and are subject to quality of the input data -- which may have gross inaccuracies.

3.2 TYPES OF CROSSINGS

There are basically five types of at-grade crossing configurations.

1. Mid-block, or isolated - Queues of vehicles stopped at the crossing do not adversely affect operations at or on significant nearby roadway components such as signalized intersections, freeway and expressway ramps, major facility driveways, or cross-walks.
2. Mid-block with nearby intersections - Queues of vehicles stopped at the crossing may significantly affect traffic operations on a nearby cross-street, ramp gore area, driveway, or in another geometric feature.

3. Adjacent - the crossing is located adjacent to an intersection between two or more streets, either in or next to the right-of-way of one of the streets entering the intersection and following its alignment.
4. Intra-intersection - the crossing is located within an intersection between two or more streets but with a light rail alignment that does not necessarily follow the alignment of any of the streets entering the intersection.
5. Median - an intra-intersection form of crossing where the light rail alignment is located in the median of one of the streets entering the intersection and follows its alignment.

3.3 TYPES OF METHODS

The types of methods available to the analyst vary widely. They range from simple calculations using a minimum amount of information to complex computer simulation modeling that needs a full range of detail concerning the proposed traffic and light rail operations.

It must be remembered that the estimates provided by each method are only as good as the input data. If the traffic volumes used are projections with a probable error of 10 percent, then the output of the method used may have an error of at least 10 percent. The more sophisticated and complex analysis methods may not be worth the effort to apply if the input data is only sketch planning level data. It may be more cost effective to use a simple manual calculation with judgement when using sketch planning level input data and leave the sophisticated analysis for a time when better input data is available.

3.4 USEFUL MANUAL CALCULATION TECHNIQUES

There are several useful manual calculation techniques that the analyst should be familiar with when evaluating at-grade light rail crossings within a traffic signal system.

- o Calculation of signalized intersection capacity using the Highway Capacity Manual (1) methods.
- o Calculation of unsignalized intersection capacity using the Highway Capacity Manual (1) methods.
- o Calculation of queue lengths based on red times and traffic flow distributions.

- o Calculation of queue discharge times using a method such as Greenshield's equation (12).
- o Knowledge of time-space diagram development techniques.

While these techniques are typically applied to sketch-planning level analyses that consider grade crossings as isolated features, they can also be useful for a variety of crossing types within traffic signal systems.

3.5 COMMONLY USED COMPUTER MODELS

The computer models have been applied to the study of the interaction of motor vehicle traffic with light rail operations.

- o The Highway Capacity Software package - for estimating delay and level of service at all configurations of at-grade crossings, for estimating arterial speeds and level of service on arterial streets.
- o PASSER II series of arterial signal system evaluation models - for evaluating operations and estimating delay of median and side-running light rail in the right-of-way of an arterial street.
- o PASSER III series of frontage road signal system evaluation models - for evaluating operations and estimating delay of median running light rail in the right-of-way of an arterial street.
- o TRANSYT-7F series of traffic signal network optimization and simulation models - for evaluating operations and estimating delay, queue length, and fuel consumption impacts at most configurations of at-grade crossings.
- o The TRAF-NETSIM series of traffic network simulation models - for evaluating operations and estimating delay, queue length, fuel consumption, and air quality impacts at most configurations of at-grade crossings.

3.6 RECOMMENDED SCREENING PROCEDURE

A screening procedure is useful to identify and assemble the data needed and the level of analysis necessary to estimate the impacts that light rail operations will have on a traffic signal

system. The following screening procedure will allow the analyst to estimate the impacts of light rail operations with a step-wise approach that will maximize results while minimizing effort.

Step 1 - Identify analysis components

What are the geometric and operational characteristics of the roadway network that will be studied? This is the network through which the light rail alignment passes. The following questions need to be addressed at this stage.

- o How are the streets laid out?
- o How many lanes wide is each street?
- o Is the operation one-way or two-way on each street?
- o Where are traffic signals located with respect to the light rail line?
- o Where are major unsignalized intersections and driveways located with respect to the light rail line?
- o How much storage space is there for queues of vehicles to form at the light rail line without blocking operations at adjacent intersections and driveways?
- o How much storage space is available for queues of vehicles to form at intersections without blocking operations on the light rail line?
- o Are the existing traffic signals coordinated, and in what manner?
- o What are the capabilities of the jurisdiction maintaining the traffic signals with respect to the issues of coordination and equipment maintenance? What level of control complexity can the operating jurisdiction reasonably be expected to handle?
- o What are the traffic signal timing parameters, such as cycle length, minimum green, clearance time, and all red time, used by the jurisdiction operating the traffic signals?
- o What type of vehicle detection does the agency operating the traffic signals use?
- o What are the hourly traffic volumes on each approach to each crossing? Identify the peak traffic volume periods.
- o What are the peak hour turning movement volumes at nearby intersections and driveways that may affect, or be affected by, an at-grade light rail crossing?

- o Does traffic flow show an affinity for one lane over other lanes, or is the approach volume evenly distributed over all lanes on the intersection or crossing approach?

What is the proposed operating practice of the light rail transit operator? The questions need to be addressed.

- o Will the policy-making board of the transit operator set guidelines on what types of crossings will be grade-separated? For example - grade separation might be mandated at all crossings of freight and passenger railroads, all crossings of interstate highways, all crossings of multi-lane controlled access freeways, and other situations.
- o What type of train control will be provided - cab signals, wayside signals, line of sight, or another method?
- o Will preemption be provided at each crossing where there are traffic signals within 200 feet as provided by the American Railway Engineering Association's Manual for Railway Engineering (14) and the Manual on Uniform Traffic Control Devices (15)?
- o What types of crossing warning devices will be used - flashing lights and gates, flashing lights only, cross-buck signs only, stop signs, traffic signals, or another device?
- o Will the light rail line segment under study be a one-way or two-way operation?
- o Can a time-space trajectory of the light rail operation be obtained early in the study process so that the effect of two-way train operations can be evaluated?
- o What will be the speed of trains across at-grade crossings? Is it enforceable?
- o What will be the headway of the light rail operation?
- o What standard of operating precision will the train operators be required to uphold? - that is, what time frame constitutes "on-time" operation versus being "late?"
- o Will light rail operations be platooned in the peak direction during peak periods?
- o What will be the maximum train length?
- o Will there be a provision for a minimum time between crossing warning device actuations - similar to setting a minimum green for traffic signals?

- o Will crossing warning devices be left in an active mode when a train dwells in a station near an at-grade crossing?

Step 2 - Lay out the problem within the study area

In this step, the analysis problem is laid out so that all available information can be reviewed in a simple and straightforward manner. A map or drawings showing the study area and the relationship between the street network and the light rail line is useful in identifying the first level of analysis. The following items should be identified during this step.

- o Which crossings are mid-block, and what is the queue storage space for each? Which of these mid-block crossings are bounded by intersections controlled by traffic signals, and are these traffic signals within a coordinated traffic signal system?
- o Does the light rail line run within a street median, and are there signalized intersections along this section of street? Are these traffic signals within a coordinated traffic signal system, and, if so, is coordination currently provided along the street with the median-running light rail?
- o Does the light rail line run next to a street, and are there signalized intersections along this street? Are these traffic signals within a coordinated traffic signal system, and, if so, is coordination currently provided along the street with the adjacent-running light rail?
- o Does the light rail line run through any intersections, such as on a diagonal from corner to corner, or when entering or leaving a median-running configuration? Is this intersection signalized, and is it within a coordinated traffic signal system?

Step 3 - Develop a time-space diagram for the light rail operation

In this step, the operation of the light rail line is laid out in detail. The primary output of this step is the pattern of crossing blockages at each prospective at-grade crossing. Of special concern to the analyst should be those crossings where there are less than 40 to 60 seconds between the start of consecutive blockages. These crossings merit special consideration including

studying the two blockages as a single blockage of great length to account for the variance in train operations.

Development of a time-space diagram for light rail operations is not difficult and can be accomplished using either the results of a train performance model or by making assumptions concerning acceleration and deceleration rates, speeds, and train lengths. Train performance models are typically used to estimate the operating characteristics of light rail trains for a variety of purposes including estimating electrical power consumption, estimating operating speeds, setting and testing the schedule, and determining the number of rail cars the system needs.

One of the outputs often provided by train performance models that is of particular use to the analyst studying the traffic impacts of at-grade light rail crossings are time-distance trajectories. These trajectories will show the cyclic pattern of train arrivals at each crossing and are useful for setting up the specific analysis at each proposed at-grade crossing.

If a suitable train performance model is not available, then the analyst can make reasonable assumptions concerning the operation of the light rail line using typical operational values such as those shown in Table 2, coupled with estimates for station dwell times and end of line layovers. As an example, assume a light rail line of 6 km (3.73 miles) in length. All trains start at Station A on 5 minute (300 second) headways, and the average operating speed is 48 km/hr (30 mph). Stations are at 2 km (1.24 mile) intervals, so there are four total stations, A - D. Layovers occur at Stations A and D. Average station dwell time is 30 seconds. There are two streets that cross this light rail line. The First Street crossing is located half way between Stations A and B, and Second Street is located one-third of the way between Stations B and C.

Table 2. Typical Light Rail Vehicle Characteristics

Characteristic	Value
Acceleration Rate	4.8 km/h/s (3 mph/s)
Service Braking Rate	4.8 km/h/s (3 mph/s)
Car length	18 m to 29 m (60 ft to 95 ft)

Although each train will not instantaneously start with an acceleration rate of 4.8 km/h/s (3 mph/s), for calculation purposes, this fact can be ignored for the moment. Similarly, for the deceleration to a stop, it is easier to set the trajectory up in a simplistic manner and then adjust

the cyclic pattern of crossing blockages later than it is to calculate the true acceleration and deceleration trajectories at less than maximum service rates. Therefore, it will take 10 seconds and 67 meters (220 ft) to accelerate from zero to 48 km/h (30 mph). Likewise, it will also take 10 seconds and 67 meters (220 ft) to decelerate from 48 km/h (30 mph) to a full stop.

The trajectory from Station A to Station B, from Station B to Station C, from Station C to Station D, from Station D to Station C, from Station C to Station B, and from Station B to Station A are all identical and described in Tables 3 and 4. The cyclic pattern between blockages at the First Street crossing is 28 seconds and 272 seconds. The cyclic pattern between blockages at the Second Street crossing is 163 seconds and 137 seconds. At the First Street crossing, opposing trains will overlap arrivals and cause the crossing to be blocked for a period that may exceed twice the single train blockage time. At the Second Street crossing, it would be an unusual occurrence for opposing trains to ever overlap arrivals.

Table 3. Example Train Time-Distance Trajectory Travel from Station A to D

Calculation Point	Incremental Time (seconds)	Elapsed Time (seconds)	Distance from Station A (meters)
Station A to 48 km/h speed	10	10	67
48 km/h speed to First St.	19	29	933
First St. to decel. point	20	49	1,866
Decel. pt. to Station B	10	59	2,000
Dwell Station B	30	89	2,000
Station B to 48 km/h speed	10	99	2,067
48 km/h speed to Second St.	13	112	2,667
Second St. to decel. point	26	138	3,933
Decel. pt. to Station C	10	148	4,000
Dwell Station C	30	178	4,000
Station C to 48 km/h speed	10	188	4,067
48 km/h speed to decel. pt.	39	227	5,933
Decel. pt. to Station D	10	237	6,000
Dwell Station D	30	267	6,000
Layover, Station D	183	450	6,000

Table 4. Example Train Time-Distance Trajectory Travel from Station D to A

Calculation Point	Incremental Time (seconds)	Elapsed Time (seconds)	Distance from Station A (meters)
Station D to 48 km/h speed	10	460	5,933
48 km/h speed to decel. point	39	499	4,067
Decel. pt. to Station C	10	509	4,000
Dwell Station C	30	539	4,000
Station C to 48 km/h speed	10	549	3,933
48 km/h speed to Second St.	26	575	2,667
Second St. to decel. point	13	588	2,067
Decel. pt. to Station B	10	598	2,000
Dwell Station B	30	628	2,000
Station B to 48 km/h speed	10	638	1,933
48 km/h speed to First St.	19	657	1,000
First St. to decel. point	20	677	67
Decel. pt. to Station A	10	687	0
Dwell Station A	30	717	0
Layover, Station A	183	900	0

These two crossings show why the acceleration and deceleration rates can be assumed to be instantaneous -- crossing blockages will either clearly occur singly, or they will occur in such a manner where prudence will counsel the analyst to assume an overlapping of arrivals.

The analyst must be aware of the normal variation in train arrivals at crossings. Unlike traffic signals where operating precision can be measured to less than one second, most light rail operations in the United States consider arriving and leaving a station within one minute of the schedule to be "on time." Berry (7) collected train headway data in the form of train arrival times at crossings within traffic signal systems on five different light rail lines in the following cities:

1. Buffalo, New York,
2. Cleveland, Ohio,
3. San Jose, California,

4. Sacramento, California, and
5. San Diego, California.

A total of 46 data sets were collected. Assuming that the scheduled headway was precise to 1.0 seconds, Berry calculated the error of each headway data set at these crossings. In fitting the data sets to a cumulative distribution function, Berry found that each headway error data set accepted a hypothesis at the 0.05 level for a Normal distribution using a Kolmogorov-Smirnov goodness-of-fit test. In only two cases did the mean error exceed one minute. However, the standard deviation of these data sets varied widely. Table 5 summarizes the mean standard deviations for Berry's data.

The results in Table 5 show that the analyst should consider the effect of normal operating variation when analyzing the traffic impacts of at-grade light rail crossings. Manual simulation techniques may be effective at introducing normally distributed error effects into an iterative analysis framework using either manual analysis methods or computer simulation.

Table 5. Mean Standard Deviations for Headways at Crossings

Time Period and Train Direction	Mean Standard Deviations (seconds)	Range of Standard Deviations (seconds)
AM Inbound Trains 12 data sets	82.65	44.4 - 162.6
AM Outbound Trains 12 data sets	100.35	22.2 - 169.8
PM Inbound Trains 11 data sets	161.02	54.6 - 406.8
PM Outbound Trains 11 data sets	132.00	29.4 - 249.0
All data sets	117.81	22.2 - 406.8

Step 4 - Estimate single train blockage times

In this step, estimate the blockage time for each type of crossing. For at-grade crossings with either passive traffic control or flashing lights only, the crossing blockage time is simply the

time it takes for the train to cross the street plus a small amount of lost time as motorists stop as the train approaches and start after the train leaves the crossing. Berry (7) contains data on blockage times at crossings where flashing light units were the only form of traffic control.

For at-grade crossings where traffic control is provided by flashing light units and gates, the blockage time can be estimated with the following equation:

$$BT = t_{aw} + t_{tc} + t_{cc} + t_1$$

where

BT = effective crossing blockage time per blockage,

t_{aw} = advance warning time in seconds,

t_{tc} = time the crossing is physically blocked by trains in seconds,

t_{cc} = crossing clearance time after trains have cleared the crossing in seconds, and

t_1 = start-up lost time in seconds.

The value of t_{aw} is normally 20 to 25 seconds at a minimum. The Manual on Uniform Traffic Control Devices (MUTCD) (15) and the American Railway Engineering Association (AREA) (14) specify a warning time of 20 seconds. The California Public Utilities Commission specifies a warning time of 25 seconds. The value of the train crossing time, t_{tc} , is a function of train speed, crossing width, number of cars in the train, and car length and is easily calculated. The crossing clearance time, t_{cc} , is usually in the range of 6 seconds. Again, this is a value specified by both the MUTCD (15) and the AREA (14). The start-up lost time, t_1 , is variable; however, examination of Berry's data (7) finds a mean start up lost time of 3.2 seconds. This data is for at-grade light rail crossings with flashing lights and gates in traffic signal systems in Sacramento and San Diego, California.

For at-grade crossings where traffic control is provided by traffic signals, the blockage time can be estimated with the following equation:

$$BT = t_a + t_{tc} + t_c + t_1$$

where

BT = effective crossing blockage time per blockage,

t_a = advance time in seconds,

t_{tc} = time the crossing is physically blocked by trains in seconds,

- t_c = clearance time after trains have cleared the crossing in seconds , and
- t_l = start-up lost time in seconds.

The values of t_a and t_{cc} are variables set by the jurisdiction operating the traffic signals controlling the crossing. At this time, the MUTCD (15) does not specify minimum values for these times. The value of the train crossing time, t_{tc} , is again a function of train speed, crossing width, number of cars in the train, and car length and is easily calculated. The start-up lost time, t_l , is again variable; however, examination of Berry's data (7) finds a mean start up lost time of 2.2 seconds. This data is for at-grade light rail crossings with traffic signal control in traffic signal systems in Buffalo, New York and San Jose, California.

When estimating the blockage time where traffic control is provided by traffic signals, the type of at-grade crossing can be important. If the crossing is within a mall environment such as those in downtown Buffalo, New York or San Diego, California, then the warning time, that is the lost time between the end of the cross-street yellow phase and the arrival of the train at the crossing, can be a minimal amount of time. However, if the light rail guideway is operating in an adjacent or median environment, then it may be prudent for the analyst to increase the warning time to include the stopping sight distance of the train. The stopping sight distance (SSD) can be estimated from the following equation:

$$SSD = (v \times t_{pr}) + (a \times t_0^2)/2$$

where

- SSD = Stopping sight distance,
- v = Train speed before brake application,
- t_{pr} = Perception - reaction time,
- a = deceleration rate of the train -- typically 4.8 km/h/s (3 mph/s), and
- t_0 = time to decelerate from the train speed to zero, approximately v/a .

One additional factor to be considered when the crossings are controlled by traffic signals is whether minimum pedestrian green times must be provided. The geometry of some crossings,

such as Church Street in downtown Buffalo, New York cause the minimum pedestrian green time calculated in the normal manner to exceed the effective crossing blockage time.

Being generous with blockage times is recommended to account for variations in train speed, track circuit or control system operation, and device operating characteristics. Overestimation of blockage times provides a measure of safety. If the results of any analysis show that an increase of 10 to 20 percent in the blockage time substantially changes the results of the analysis, then additional mitigatory analyses should be undertaken. Only for long blockages, such as those measured on the San Diego Trolley that were in excess of 100 seconds, should lesser increases be accepted.

Step 5(A) - Perform a cursory queue length study at each mid-block crossing and critical intersection approach

The purpose of this step is to winnow out the minor crossings where traffic operations will not be significantly affected and to identify what parts of the street network need additional study. Unless traffic volumes and crossing blockage times are high and train headways are low or two trains pass through the crossing over a short time period, crossing capacity will not typically be a controlling factor at mid-block crossings. The effective green time to cycle length ratio (g/C ratio) of most at-grade light rail crossings is greater than most green time to cycle length ratios at signalized intersections.

Since crossing capacity is not typically a problem at mid-block crossings, average stopped delay encountered by motor vehicles at the crossing is also not typically a problem. The most likely motor vehicle impact at mid-block crossings results from queuing. Any of the procedures outlined in Section 2.4.4 can be applied at this point. However, a strategic decision at this point can save the analyst time and effort.

A quick check of the potential queuing caused by light rail operations can be performed by multiplying the average number of vehicles arriving at the crossing during the blockage time by 2.0 and adjusting for lane distribution. If this queue estimate does not show that any significant nearby intersections or driveways are likely to be blocked, then a similar check should be made of queuing resulting from traffic signal or stop sign operations.

For the traffic signal estimate, the minimum reasonable green time plus clearance interval, and hence, maximum red time should be assumed for the street approach that may queue across the light rail crossing. Queuing estimates resulting from stop signs are dependent upon whether the intersection is an all-way stop or a stop with other, uncontrolled approaches.

If these queue estimates do not show that the light rail crossing is likely to be blocked, then light rail operations probably will not adversely affect traffic operations at these at-grade crossings. If, however, queue estimates do show that either the nearby intersection or the crossing may be blocked, then it is appropriate to study the crossing and street segment in additional detail to determine feasible mitigation strategies.

For an additional measure of safety, maximum back of queue calculations can be substituted for the queue at end of red calculations given in the preceding paragraphs. The maximum back of queue calculation is only slightly longer and will yield a greater queuing distance at all arrival percentiles than the back of queue on red estimate.

The alternative to these simple, straight forward estimating procedures is to use a computer-based traffic simulation program such as TRANSYT-7F or Traf-NETSIM. These programs will give estimates of average queue lengths. If the jurisdiction that maintains and times the traffic signals bounding the street segment containing the mid-block crossing uses either of these programs, then the analyst can probably reduce the coding time of the programs by starting with the jurisdiction's model. Again, queuing that results from the crossing blockage and any nearby traffic signals should both be checked. After determining which intersections and at-grade crossings exhibit undesirable queue interactions, further analysis can be planned.

Step 5(B) - Perform a cursory intersection capacity and queuing study on all left turn lanes and street approaches at intra-intersection crossings obliquely traversing intersections

The purpose of this step is to determine if proposed at-grade light rail crossings through intersections may create adverse intersection capacity constraints and to estimate if the queues of vehicles generated on the intersection approach legs to such crossings may exceed the storage space available. The key assumption of this step is that the intersection will either be fully gated or controlled by a traffic signal. A study of the intersection capacity is easily performed using any one of several computerized intersection evaluation routines such as the Highway Capacity

Software, PASSER II, TRANSYT-7F, Traf-NETSIM, or the TEXAS model. TRANSYT-7F, Traf-NETSIM, and the TEXAS model will also generate average queue lengths either based on the queue at the end of red or the maximum back of queue.

The setup of the problem within each of the computer programs is similar. The intersection geometry is coded in the normal way. Traffic signal operations are assumed even if the intersection is protected by flashing lights and gates. Left turn phasing is typically assumed to be protected only -- not protected - permitted because of safety issues associated with clearing the intersection on the approach of a train. Left turns may lead or lag depending on local conditions. The crossing of the light rail train is modeled by adding a dummy phase to the traffic signal phase sequence modeled. The length of the dummy phase corresponds to the length of the crossing blockage and should consider whether the transit operator will have stopping sight distance rules in effect at these types of crossings. If the model used does not estimate queue lengths, then the back of queue at end of red or maximum back of queue can be estimated for each lane or lane group using any of the methods outlined in Section 2.4.4.

Step 5(C) - Perform a cursory intersection capacity and queuing analysis on left turn lanes and cross-street approaches at crossings within street medians

The purpose of this step is to determine if proposed median-running at-grade light rail crossings through intersections may create adverse intersection capacity constraints and to estimate if the queues of vehicles generated on the intersection approach legs to such crossings may exceed the storage space available. The key assumption of this step is that the intersection will be controlled by a traffic signal. Like the intra-intersection, a study of the intersection capacity is easily performed using any one of a number of computerized intersection evaluation routines such as the Highway Capacity Software, PASSER II, TRANSYT-7F, Traf-NETSIM, or the TEXAS model. TRANSYT-7F, Traf-NETSIM, and the TEXAS model will also generate average queue lengths either based on the queue at the end of red or the maximum back of queue.

The setup of this problem within each of the computer programs is similar. The intersection geometry is coded in the normal way. For the sake of discussion, the median-running light rail operations are considered to parallel the "main-street." The cross-street is considered to be the "minor" street. Left turn phasing is typically assumed protected only -- not protected -

permitted because of safety issues associated with clearing the intersection of left turning vehicles on the approach of a train. Left turns may lead or lag depending on the light rail operations. The crossing of the light rail train is modeled by adding sufficient green time to the "main-street" through phase of the traffic signal phase sequence modeled. The length of the "main-street" green phase, as a minimum, must correspond to the length of the crossing blockage and should consider whether the transit operator will have stopping sight distance rules in effect at these types of crossings. If the model used does not estimate the left turn and cross-street queue lengths, then the back of queue at end of red or maximum back of queue can be estimated for each lane or lane group using any of the methods outlined in Section 2.4.4.

Step 5(D) - Perform a cursory queuing analysis on right turn lanes and cross-street approaches at crossings adjacent to signalized intersections

The purpose of this step is to determine if proposed at-grade light rail crossings adjacent to intersections may create adverse intersection capacity constraints and to estimate if the queues of vehicles generated on the intersection approach legs to such crossings may exceed the storage space available. The key assumption of this step is that the intersection will be controlled by a traffic signal. The crossing itself may or may not be controlled by flashing lights and gates. Like the intra-intersection and median crossings, a study of the intersection capacity is easily performed using any one of several computerized intersection evaluation routines such as the Highway Capacity Software, PASSER II, TRANSYT-7F, Traf-NETSIM, or the TEXAS model. TRANSYT-7F, Traf-NETSIM, and the TEXAS model will also generate average queue lengths either based on the queue at the end of red or the maximum back of queue.

The setup of this problem within each of the computer programs is similar. The intersection geometry is coded in the normal way. For the sake of discussion, the adjacent-running light rail operations are considered to parallel the "main-street." The cross-street is considered the "minor" street. Left turn phasing is typically assumed protected only -- not protected - permitted because of safety issues associated with clearing the intersection of left turning vehicles on the approach of a train. Left turns may lead or lag depending on the light rail operations. Right turns are typically assumed controlled by green, yellow, and red arrow signals and allowed as a "protected-only" phase because of safety issues associated with right turning

vehicles sideswiped by a train approaching from the rear. Right turns, like left turns, may lead or lag depending on the light rail operations. The crossing of the light rail train is modeled by adding sufficient green time to the "main-street" through phase of the traffic signal phase sequence modeled. The length of the "main-street" green phase, as a minimum, must correspond to the length of the crossing blockage and to the time necessary to serve the protected main-street right turn movement crossing the light rail guideway. It should also consider whether the transit operator will have stopping sight distance rules in effect at these types of crossings. If the model used does not estimate the left turn, right turn, and cross-street queue lengths, then the back of queue at end of red or maximum back of queue can be estimated for each lane or lane group using any of the methods outlined in Section 2.4.4.

Step 6(A) - Develop strategies to mitigate undesirable queue interactions resulting from mid-block crossing operations

The key purpose of this step is to determine the appropriate technique for mitigating the undesirable queues that may be related to mid-block crossing operations. The first task in this step is to determine the cause of the queuing.

- a. Light rail crossing blockages
- b. Signalized intersection operations
- c. An unsignalized intersection with insufficient service times
- d. The geometry of the roadway network.

If the queuing is the result of light rail crossing blockages, the following questions apply.

- o What impact is it having on the roadway network?
- o Is the upstream intersection signalized?
- o Is it within a progressive arterial traffic signal system?
- o Is it within a traffic signal network?
- o What is the relationship of the upstream intersection with other traffic signals in the system?
- o Can the traffic signal be preempted?
- o Can priority control be implemented?
- o What level of disruption to traffic signal operations can be tolerated?

- o Is the upstream intersection (or major driveway) unsignalized? Can it be signalized? If signalized, can it be preempted without disrupting the rest of the traffic signal system?
- o Is the street segment that contains the at-grade light rail crossing so short that the queue spill-back from the crossing blocks left turn and right turn approaches from the major street the short street segment tees into?

If the queuing is the result of nearby signalized intersection operations, the following questions apply.

- o What impact is it having on the at-grade crossing and other intersections within the roadway network?
- o Is the signalized intersection within a progressive arterial traffic signal system? Is it within a traffic signal network? What is the relationship of the signalized intersection with other traffic signals in the system?
- o Can the traffic signal be preempted?
- o Can priority control be implemented?
- o What level of disruption to traffic signal operations can be tolerated?
- o Can the red time on the intersection approach downstream from the at-grade crossing be minimized to reduce queue lengths?
- o Can the traffic signal be double cycled with respect to the rest of the traffic signal system to reduce red time and thereby queue lengths?

If the queuing is the result of nearby unsignalized intersection or major driveway operation, the following questions apply.

- o What impact is it having on the at-grade crossing and other intersections within the roadway network?
- o Does traffic control at the unsignalized intersection need to be reevaluated to increase the service rate of vehicles clearing the at-grade light rail crossing?
- o Can the driveway be closed and traffic diverted to another route?

If the queuing is the result of roadway geometry, the following questions apply.

- o Can additional geometric enhancements mitigate the queue formation?

- o Can right turn lanes be constructed so that right turns occur in a free-flow mode from behind a protective island?
- o Can left turns be prohibited and routed over a different path?
- o Can the crossing be relocated adjacent to the intersection? Can it be moved further away?

Each of these questions in this task narrows the analysis technique that is appropriate to estimating the impact of the at-grade light rail crossing. For such items as extending queue storage areas or adding lanes, it is appropriate to first check the adequacy of storage using manual calculation techniques. Where the queuing problem includes Stop or Yield sign control, Traf-NETSIM is the most appropriate analysis tool. For strategies that involve changing the traffic signal operation, an optimization program such as PASSER II or TRANSYT-7F may be appropriately used first followed by a simulation program such as TRANSYT-7F or Traf-NETSIM. For strategies that physically relocate a traffic movement, reassignment of the affected traffic volume should be carefully performed considering such factors as travel time, directness of route, and driver acceptance of the new route before analysis.

Step 6(B) - Develop strategies to mitigate intersection capacity constraints and undesirable queue interactions at intra-intersection crossings obliquely traversing intersections

The purpose of this step is to determine the appropriate techniques for mitigating the intersection capacity constraints and undesirable queue lengths at intra-intersection light rail crossings. To mitigate capacity constraints, either crossing blockage times must be reduced or, more likely, pavement will have to be added in the form of additional through or turn lanes for critical movements. To mitigate queuing problems in the turn lanes, either additional lane length will be necessary, or additional turning lanes.

Although PASSER II, TRANSYT-7F, Traf-NETSIM, and the TEXAS model can be applied to this type of problem, if intersection capacity is the only impact to be mitigated, then the Highway Capacity Software may be the simplest approach to the problem. If, on the other hand, queues and capacity constraints are both involved, then an isolated intersection modeled with TRANSYT-7F or Traf-NETSIM will be the best approach. While the TEXAS model can be applied, its data intensiveness and accuracy is lost in the rough precision of the light rail

environment. Finally, if only queues are involved, manual calculation techniques may be sufficient to provide workable alternatives.

Step 6(C) - Develop strategies to mitigate intersection capacity constraints and undesirable queue interactions on left turn lanes and cross-street approaches at crossings within street medians

The purpose of this step is to determine the appropriate techniques for mitigating the intersection capacity constraints and undesirable queue lengths in left turn lanes and on cross-street approaches at light rail crossings within street medians. Like the intra-intersection crossings, to mitigate capacity constraints, either crossing blockage times will have to be reduced or, more likely, pavement will have to be added in the form of additional through or turn lanes for critical movements. Also, to mitigate queuing problems in the left turn lanes and on cross-street approaches, either additional lane length will be necessary, or additional lanes may be needed.

At this point, depending on the left turn operation, if intersection capacity is the only impact to be mitigated, then the Highway Capacity Software or PASSER III may be the simplest approach to the problem. If, again, queues and capacity constraints are both involved, then an isolated diamond interchange modeled with TRANSYT-7F or Traf-NETSIM will be the best approach. If only exterior interchange queues are involved, manual calculation techniques may be sufficient to provide workable alternatives.

If queues are the problem and the left turns are concurrent, one technique that should not be overlooked, however, is to use PASSER II or TRANSYT-7F and change the phase sequence from concurrent leading to concurrent lagging or vice versa. The effect of this change cannot be easily measured with either the Highway Capacity Software or with manual calculation techniques.

Step 6(D) - Develop strategies to mitigate undesirable queue interactions on right turn lanes and cross-street approaches at crossings adjacent to signalized intersections

The purpose of this step is to determine the appropriate techniques for mitigating undesirable queue lengths in right turn lanes and on cross-street approaches at light rail crossings adjacent to signalized intersections. The primary mitigation techniques for queuing problems in the right turn lane and on cross-street approaches is to add either additional lane length or additional lanes. Although TRANSYT-7F and Traf-NETSIM can be applied to this type of

problem, if only queues are involved, manual calculation techniques may be sufficient to provide workable alternatives.

Step 7 - Study signalized intersection and at-grade light rail crossing interactions using simulation

The purpose of this step is to take each full street network and traffic signal system and integrate the appropriate mitigated light rail crossing types into a cohesive simulation problem. Using either TRANSYT-7F or Traf-NETSIM, the analyst should develop the network appropriate to the street network and signal system being studied. All mid-block crossings, intra-intersection crossings, median-running light rail sections, and adjacent-running light rail sections should be included in the simulation network.

To minimize total network size, each individual traffic signal system should be simulated separately. Traffic signal sub-system configurations may allow further reduction in each study network. The purpose behind minimizing network size is twofold: a reduction in coding and debugging the software, and faster computational times resulting in the ability to make more simulation runs.

The output of the simulation runs should be carefully checked to make sure that mitigation techniques perform as expected. Stop line flow profiles, platoon progression diagrams, and time-space diagrams should be reviewed. The trajectory of light rail trains should be checked. Clearance phases should be checked against time-space diagrams to make sure they are properly offset. Transitions between phase sequences should be checked. All queue data should be reviewed, especially when using TRANSYT-7F, since a queue blocking an intersection approach is not explicitly modeled as a blockage. Finally, offsets in the traffic signal system should be checked to determine if slight modifications, not identified in the optimization process, might result in increased efficiency of the traffic signal system.

The final task in this step is to run the simulation model over again and again, varying the light rail trajectory somewhat to model the natural variation in train operations. If using TRANSYT-7F, this will be the most that can be done without totally recoding the network. If using Traf-NETSIM, then the random number seed can be changed to automatically introduce randomness into the simulation. This process should cover the expected bounds of the light rail operation and is essentially a sensitivity analysis. At the end of this process, the analyst should

be able to grasp the impact of at-grade light rail operations on the street network and traffic signal system.

Step 8 - Review the results of the analysis for reasonableness

The last step in the screening procedure is to check all of the results for reasonableness. In part, that is the purpose of making multiple simulation runs that vary the light rail trajectories; but this step really should go beyond that to a careful, thoughtful review of the analysis process so that the analyst and, eventually the light rail patron and motorist, are comfortable with the end decisions in the process.

4.0 TYPICAL APPLICATION OF MODELS TO PROBLEMS

4.1 INTRODUCTION

In this section, application of five computer models to the evaluation of at-grade light rail crossings within traffic signal systems will be discussed. In each case, it is assumed that the reader is familiar with the models:

1. The Highway Capacity Software program,
2. PASSER II,
3. PASSER III,
4. TRANSYT-7F, and
5. Traf-NETSIM.

These models are ranked in order of complexity, and to some degree, usefulness as simulators of the light rail environment. Only the basic changes in application, approach, or coding are addressed.

4.2 HIGHWAY CAPACITY SOFTWARE

The Highway Capacity Software (HCS) (10) can be applied to all types of at-grade light rail crossings so long as each crossing is considered on an individual basis. The Highway Capacity Software is the simplest analysis tool after manual calculation techniques, and sometimes, is even easier to apply than a manual mathematical calculation. The primary shortcomings of the software are that:

- o It only considers individual intersections,
- o It does not provide queuing estimates, and
- o Each analysis only applies to a single traffic signal cycle length.

Modeling a mid-block crossing with the Highway Capacity Software is simple. The operation is simply coded as a two-phase traffic signal where each blockage to blockage in the cyclic pattern of crossing blockages makes up an individual traffic signal cycle length. Berry (7) validated the delay equation used by the Highway Capacity Software for light rail headways up to 15 minutes in length on light rail guideways with two-way operations.

Modeling an intra-intersection crossing with the Highway Capacity Software is perhaps the most difficult of applications. This is because of the extra phase needed to account for light rail blockages. Three-leg intersections, which are analyzed as four-leg intersections due to the additional phase required for light rail blockages, can be modeled explicitly. However, four-leg intersections cannot be analyzed because the current version of Highway Capacity Software cannot analyze five-leg intersections (four-leg intersections must be analyzed as five-leg intersections because an extra phase is needed to allow for light rail blockages). Five intersection leg versions of the Highway Capacity Manual (1) signalized intersection capacity method are available. These computer programs, that produce results similar to the Highway Capacity Software, can be used to gain the extra light rail phase necessary for the delay calculations.

Modeling median- and adjacent-running light rail crossings is easier than the intra-intersection crossing because the light rail operation only results in an extended green for the main-street through movements, and the Highway Capacity Software computer program only sees this as a long green phase. Like the mid-block crossing, the cyclic pattern of crossing blockages and normal signal cycles must be considered together to get an accurate representation of the intersection operation.

4.3 PASSER II

PASSER II can be applied to all types of at-grade light rail crossings. Mid-block crossings are considered on an individual basis. Intra-intersection crossings and crossing involving median- and adjacent-running light rail can be studied individually or in arterial systems.

In terms of simplicity, PASSER II follows the Highway Capacity Software as the next simplest analysis tool after manual calculation techniques. The arterial evaluation capabilities of PASSER II are one of the primary strengths of this program. The primary shortcomings of the software are listed below.

- o It studies only individual signalized intersections and arterial traffic signal systems.
- o It does not provide queuing estimates.
- o Each analysis only applies to a single traffic signal cycle length. Cycle length flexibility is not permitted within a single modeling run.

- o The maximum cycle length of the program is limited to 150 seconds for optimization and 300 seconds for evaluation.

Modeling a mid-block crossing with PASSER II is simple. The operation is simply coded as a two-phase isolated traffic signal where each blockage to blockage in the cyclic pattern of crossing blockages makes up an individual traffic signal cycle length. Each component of the cyclic pattern is analyzed separately. An average weighting of the results of each component is performed to estimate the overall impact of the crossing.

Modeling intra-intersection crossings with PASSER II is limited. Only isolated intersections can be studied because model limitations may require multiple computer runs to develop usable estimates. The extra phase is needed to account for light rail blockages. Three-leg intersections, which are analyzed as four-leg intersections due to the additional phase required for light rail blockages, can be modeled explicitly. However, four-leg intersections cannot be analyzed because the current version of PASSER II cannot analyze five-leg intersections (four-leg intersections must be analyzed as five-leg intersections because an extra phase is needed to allow for light rail blockages). Five intersection leg intersections can be studied implicitly by using two four-leg intersection PASSER II runs. In the first run, the main-street red phase is increased to account for the cross-street green and clearance phase and for the light rail crossing blockage. In the second run, the cross-street red phase is similarly increased. By taking the measures of impact for intersection approaches with the increased red phases from both PASSER II runs and combining them on a "weighted" basis, an estimate of the impact of an intra-intersection can be estimated. Simulation with a program such as TRANSYT-7F or Traf-NETSIM should be used to check the operational results of this application.

PASSER II may be the best program for setting up analysis on median- and adjacent-running light rail crossings because they inherently involve arterial traffic signal operation. A median-running light rail analysis requires only one basic assumption, the design of the median is such that concurrent leading or lagging left turns are possible without conflict. If the median design will not allow safe concurrent left turn operation, then PASSER III should be used and each signalized intersection should be modeled as a small diamond interchange.

The key points in setting up a PASSER II analysis for median-running light rail operations are listed below.

- o Use a time-space diagram for the rail operations (see Section 3.6) to determine preliminary arterial speeds and traffic signal offsets.
- o Determine if the station dwell times or other aspects of the light rail operation make it reasonable for the light rail trajectory to stay within a single arterial street green band drop from one arterial street green band to the next arterial street green band.
- o Use only protected left turns -- either concurrent lagging or concurrent leading.
- o Do not use lead-lag left turns unless cross-street impacts are inconsequential. The lead-lag operation of left turns may provide a superior arterial green band in normal arterial traffic signal systems, but the through green phase necessary for light rail operations may result in arterial green time being provided even when there is no arterial traffic demand. Lead-lag left turn operations can result in inefficient arterial operation where median-running light rail is present.
- o Add arterial green time to cover the stopping sight distance of the train as the minimum warning time if no guidance on train control is provided by the transit operator.

Multiple PASSER II runs may be useful, depending on the light rail headways and trajectories, to provide optimal arterial operation for traffic signal cycles that do not need to accommodate light rail operations. If this type of strategy is used, then it is recommended that simulation with a program such as TRANSYT-7F, or Traf-NETSIM be used to check the operational results of the arterial traffic signal system.

The adjacent-running light rail analysis is only slightly more difficult than the median-running light rail analysis. Whereas the median-running light rail analysis can be performed with a minimum of one PASSER II run, adjacent-running light rail will require a minimum of two PASSER II runs. The key points in setting up the adjacent-running PASSER II analysis are listed below.

- o Use a time-space diagram for the rail operations (see Section 3.6) to determine preliminary arterial speeds and traffic signal offsets.
- o Determine if the station dwell times or other aspects of the light rail operation make it reasonable for the light rail trajectory to stay within a single arterial street green band drop from one arterial street green band to the next arterial street green band.

- o Use only protected right turns -- either lagging or leading.
- o Do not use right-turn-on-red operation.
- o Add arterial green time to cover the stopping sight distance of the train as the minimum warning time if no guidance on train control is provided by the transit operator.
- o For one PASSER II run, use only the left and right arterial movements on the intersection approaches next to the light rail line. For the second PASSER II run, use only the left and through arterial movements on the intersection approaches next to the light rail line.

The first PASSER II run will provide the arterial green time necessary to serve the protected right turns. Adding this green time to the crossing blockage time for the second PASSER II run will provide the minimum arterial through movement green time for the through movement adjacent to the light rail line. A third PASSER II run can be performed to optimize arterial traffic flow for traffic signal cycles that do not need to accommodate light rail operations. It is recommended that simulation with a program such as TRANSYT-7F or Traf-NETSIM be used to check the operational results of the arterial traffic signal system for adjacent-running light rail when using multiple PASSER II runs as the basis for operational development.

4.4 PASSER III

Conceptually, PASSER III is nearly perfectly designed to analyze median-running light rail within an arterial traffic signal system. The frontage roads act as the parallel arterial on each side of the median with the light rail guideway being the "freeway." For streets with wide medians where concurrent left turn movement paths would overlap and interlock, the four-phase TTI diamond interchange signal sequence that is one option in PASSER III provides the solution to the problem as no other computer program can. The key points in setting up a PASSER III analysis for median-running light rail operations are listed below.

- o Use a time-space diagram for the rail operations (see Section 3.6) to determine preliminary arterial speeds and traffic signal offsets.

- o Determine if the station dwell times or other aspects of the light rail operation make it reasonable for the light rail trajectory to stay within a single arterial street green band drop from one arterial street green band to the next arterial street green band.
- o Use only signal sequences that minimize or prevent storage of vehicles in the interior area of the interchange. The interior must be clear for light rail operations without having to add explicit clearance phasing.
- o Add arterial green time to cover the stopping sight distance of the train as the minimum warning time if no guidance on train control is provided by the transit operator.

Like PASSER II, multiple PASSER III runs may be useful, depending on the light rail headways and trajectories, to provide optimal arterial operation for traffic signal cycles that do not need to accommodate light rail operations. If this type of strategy is used, then that simulation with a program such as TRANSYT-7F or Traf-NETSIM should be used to check the operational results of the arterial traffic signal system. PASSER III has a maximum cycle length restriction of 150 seconds.

4.5 TRANSYT-7F

TRANSYT-7F is a powerful optimization and simulation tool that is flexible enough to be useful for light rail applications. It is a tool that can evaluate single mid-block at-grade crossings, mid-block at-grade crossings within traffic signal systems, intra-intersection light rail crossings, median-running light rail crossings, and adjacent-running light rail crossings. With planning, TRANSYT-7F can be used to evaluate the three primary light rail operational strategies.

- o Running within a traffic signal system, but without interfacing with it. An example of this type of operation is Greater Cleveland Regional Transportation Authority's Shaker Heights median-running operation. The city of Shaker Heights, Ohio sets up the traffic signal operation on Shaker Boulevard, and there is no communication between the light rail signal system and the traffic signal system.
- o Running within a traffic signal system with "priority" control. This is a form of traffic signal preemption where red phases may be truncated or green phases extended on a "call" from an approaching light rail train. An example of this type of operation is

along the Guadalupe corridor of the Santa Clara County Transportation Agency's light rail line in San Jose, California.

- o Running through a traffic signal system with full railroad-type traffic signal preemption where the approaching train places a "call" to the traffic signal controller and a special phase sequence is implemented to clear the at-grade crossing of any vehicles that may be on the light rail guideway. An example of this type of operation can be found along the San Diego Trolley's South line that parallels Interstate Highway 5 in Chula Vista, California. Full preemption is provided where the light rail line crosses E Street and H Street in Chula Vista.

In practice, TRANSYT-7F is a program that has been used to evaluate the traffic impacts associated with light rail operations in Dallas, Texas and Buffalo, New York.

In Dallas, DART consultants used TRANSYT-7F for:

- o Evaluation of median operations in the Lancaster Road and Jefferson Boulevard traffic signal systems in 1987 (16),
- o Evaluation of transitway mall operations within the Dallas Central Business District traffic signal system in 1988 (17), and
- o Evaluation of mid-block crossings within the North Central Expressway Corridor traffic signal system in 1990 (8).

In each case, TRANSYT-7F proved to be a versatile tool for evaluation. The primary limitations of the model, the maximum traffic signal cycle length and the number of allowable intervals, were overcome by creative application of the model. The TRANSYT-7F results were sufficient to result in further definitive evaluation using Traf-NETSIM.

Modeling a mid-block crossing with TRANSYT-7F is simple. The at-grade light rail crossing is coded as a two- or four-phase isolated traffic signal where each cross-street through movement and each crossing blockage in the cyclic pattern of crossing blockages make up an individual traffic signal phase. The two-phase pattern corresponds to one blockage for each headway set, and the four-phase pattern corresponds to two blockages for each headway set. The green phases associated with the light rail blockage will need movements coded; however, these movements should be coded with traffic volumes set to zero. Because TRANSYT-7F will allow

coding up to 11 discrete phases, post-run computations to arrive at the final measures of impact estimate are less than for the Highway Capacity Software, PASSER II, or PASSER III.

Modeling intra-intersection crossings with TRANSYT-7F is also quite simple unless the intersection has five or more controlled legs. For this application, the light rail blockage is coded into the intersection as an additional green phase but without movements associated with traffic volumes. The five-leg intersection with an intra-intersection crossing may need to be coded with some or all of the left turn movements being concurrent rather than overlapped. This adjustment is necessary if the 11 phases that TRANSYT-7F allows the user to code are not adequate to model the operation of the intersection.

For both mid-block and intra-intersection crossing types, integration within a traffic signal system is only a matter of coding the crossing nodes as part of the overall system. To maintain a proper light rail trajectory through the signal system, the "signal offset" relationships between the light rail crossing nodes must remain fixed. The remaining signalized intersection nodes can be allowed to optimize around the fixed offset relationships or they can be fixed for evaluative purposes.

TRANSYT-7F is useful for most median-running light rail scenarios:

- o Median-running within an arterial traffic signal system and
- o Median-running within a grid traffic signal system where progression may be required along the cross-street routes.

Coding TRANSYT-7F for median-running evaluations varies depending on whether the left turns can operate concurrently or if they must be operated separately. If the left turns can be operated concurrently, then the problem setup is identical to coding an arterial street for progressive movement. No special coding is necessary other than providing adequate arterial green time for the light rail operation to clear each cross-street. As stated previously, PASSER II outputs can give an excellent starting point for setting up the fixed relationship between the arterial intersections that is necessary for median-running light rail.

If the left turns cannot be operated concurrently, then each cross-street intersection along the median-running light rail line should be coded as a tight diamond. Using PASSER III outputs as a starting point for identifying the proper phase sequence will significantly reduce the analysis

time. Again, the light rail trajectory through the traffic signal system can be maintained by fixing the offset relationships of the individual arterial intersections. The key points in setting up a TRANSYT-7F analysis for median-running light rail operations are the same as those described for the PASSER II and PASSER III applications.

Coding TRANSYT-7F for adjacent-running evaluations is similar to the median-running coding except that right turns from the arterial street are explicitly coded, phased, and timed. Except for this aspect, the problem setup is identical to coding an arterial street for progressive movement. Like the median-running light rail problem, PASSER II outputs can give an excellent starting point for setting up the fixed relationship between the arterial intersections that is necessary for adjacent-running light rail. The key points in setting up a TRANSYT-7F analysis for adjacent-running light rail operations are the same as those described for PASSER II applications.

In all of the TRANSYT-7F examples, one technique that normally will be needed is the combination of multiple TRANSYT-7F runs. Because TRANSYT-7F models a single traffic signal cycle that is expanded out to represent average hourly measures of impact, an analyst can take individual TRANSYT-7F runs and combine them as necessary to construct an hour of traffic signal cycles.

The key to applying this technique is consistency. Equal intervals should be used -- ideally the traffic signal cycle length. Traffic volumes should not be varied. Once optimized, all evaluations should be done in the simulation mode of the program so that the offsets of each of the signalized intersections do not vary with the different traffic signal cycles being modeled. As long as the basic parameters of the traffic signal system are fixed, the analyst can vary the light rail operations and the traffic signal sequences at adjacent signalized intersections to account for priority or preemptive control strategies.

All outputs should be carefully evaluated for consistency with the results being averaged or summed, depending on the measure of impact. Stop line flow profiles and platoon progression diagrams are extremely useful in making this reasonability check. If in doubt with the impact of a proposed measure after performing an in-depth TRANSYT-7F analysis, the analyst should check their results with a true traffic simulation program such as Traf-NETSIM.

4.6 TRAF-NETSIM

As powerful and flexible as TRANSYT-7F can be in evaluating the traffic impacts of at-grade light rail operations within traffic signal systems, there are times when it is insufficient for obtaining definitive results:

- o When complex clearance intervals are involved,
- o When the full effect of traffic-actuated signal control needs to be assessed,
- o When the measures of impact of other, simpler, evaluation techniques indicate that a borderline situation may exist between no adverse impact and adverse impact, and
- o When a graphic simulation is needed.

The best available tool for these cases is Traf-NETSIM. It is a microscopic traffic simulation model that can be used to evaluate each case previously discussed for other evaluation techniques. Some of the most valuable aspects of Traf-NETSIM are its abilities:

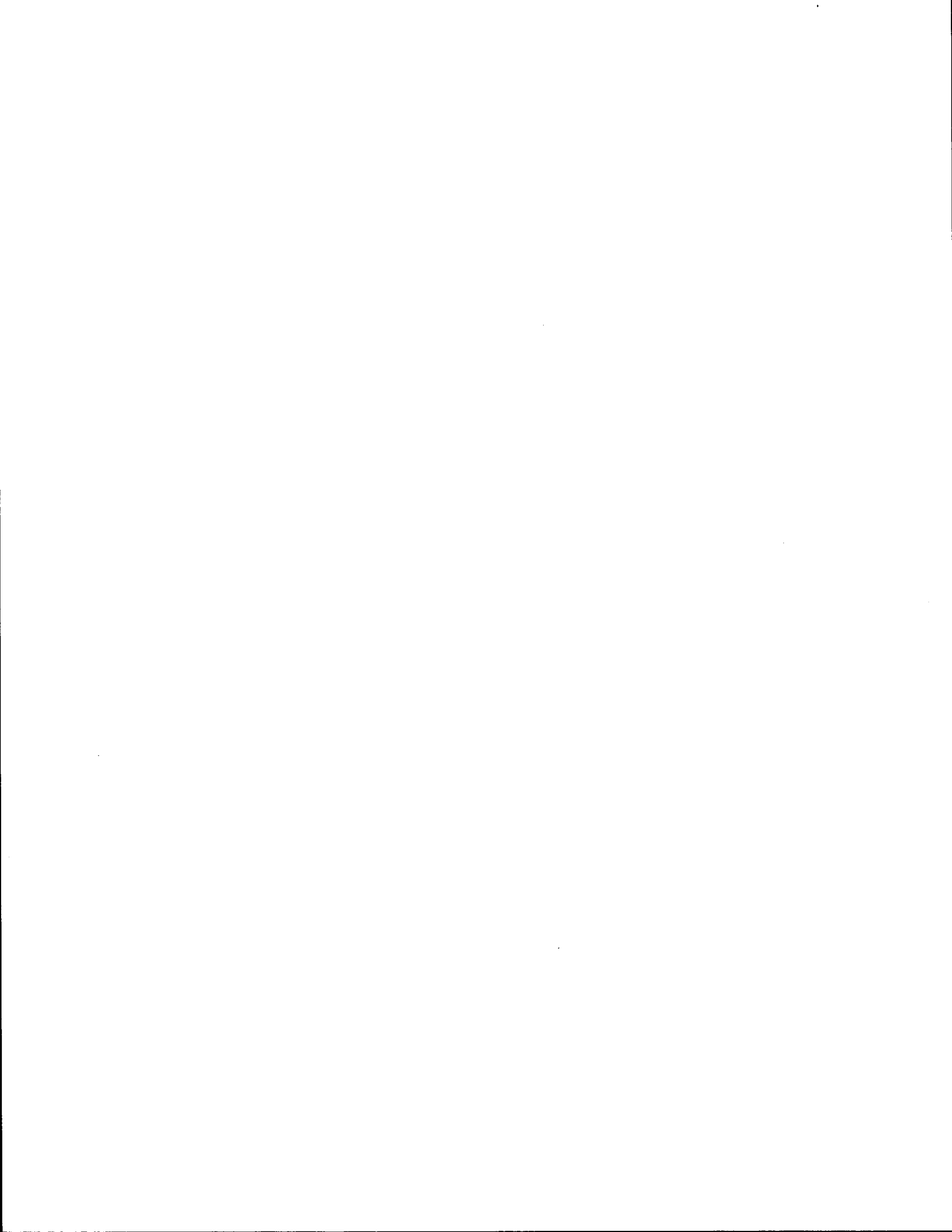
- o Emulate 8-phase pretimed and full-actuated traffic signal control,
- o Simulate traffic flow over an extended time period, rather than in single signal cycle "snapshots" like TRANSYT-7F and the PASSER programs,
- o Transition between different phase sequences with varying transition lengths,
- o Change model randomness by using different random number seeds so that multiple Traf-NETSIM runs can be used to develop probabilistic distributions of the measures of impact, and
- o Graphically illustrate the operations being modeled on the video monitor screen.

The primary shortcomings of Traf-NETSIM include the following items.

- o The complexity of the model requires a firm grasp of traffic operations and traffic signal operation.
- o The model is not easy to code, even with the software screens and editors that have been included in the model since its initial microcomputer release in 1986.
- o Some signalized intersection types -- especially those with more than four approach legs--cannot be analyzed under all full-actuated conditions without simplifying assumptions.
- o The model is strictly a simulation model with no optimization capabilities. As such, other means of developing initial traffic signal timings and offsets, such as using

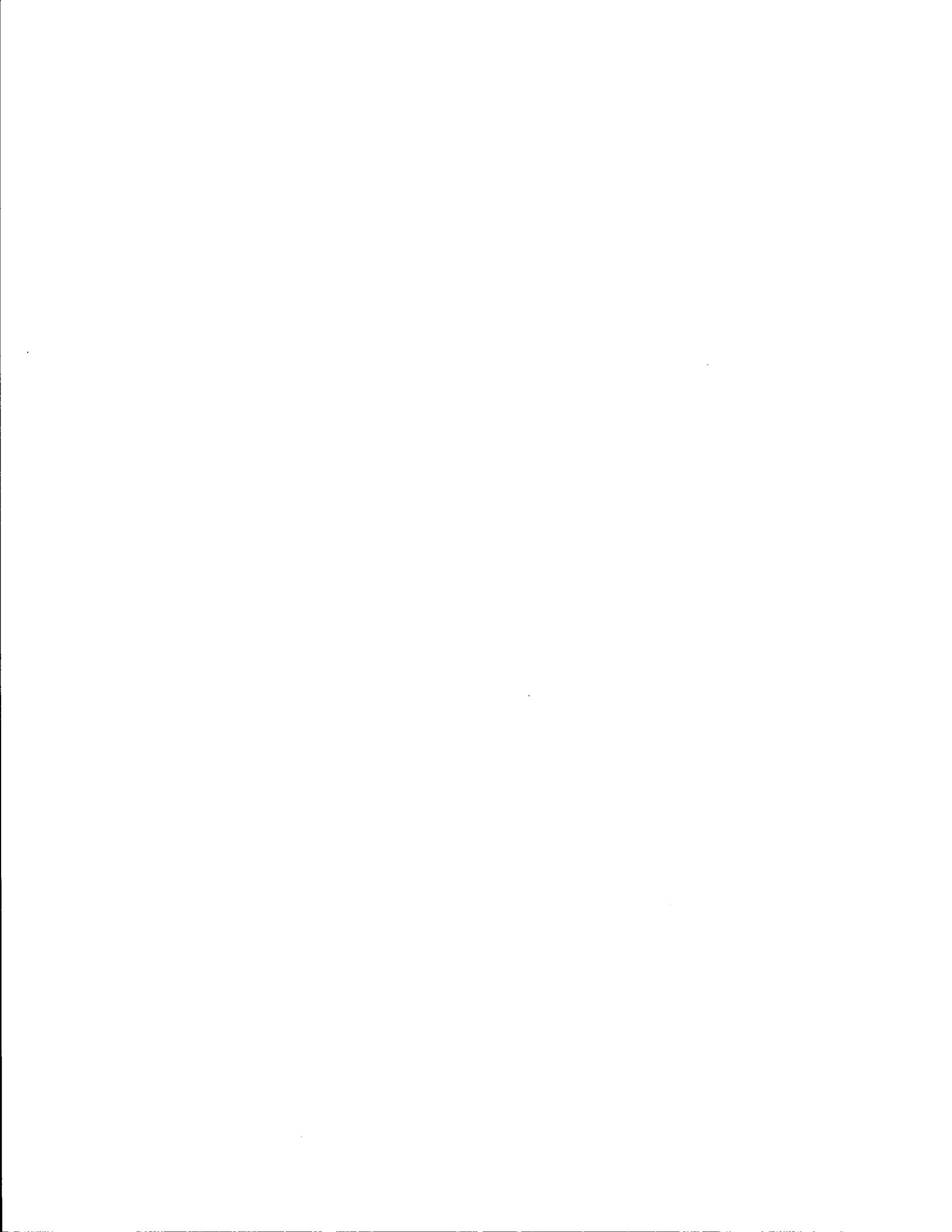
TRANSYT-7F or either PASSER program, is a necessary step in the process of using Traf-NETSIM.

Application of Traf-NETSIM is addressed in Interim Report 2 (18) and will not be addressed here other than to emphasize that for median- and adjacent-running light rail, the key points in setting up the problem are the same as setting up either the PASSER II or TRANSYT-7F evaluation.



5.0 SUMMARY AND RECOMMENDATIONS

This report has identified and recommended measures of impact that are applicable to the operation of at-grade light rail crossings within traffic signal systems. The key point in identifying measures of impact was to maintain consistency with traffic signal measures of impacts. The recommended measures of impact included average delay and length of queue assuming an n^{th} percentile vehicle arrival rate. It was then illustrated how the analyst could apply both manual calculation methods and computer models to estimate these measures of impact. Included in the discussion was a screening procedure that is designed to minimize total work effort by identifying impacts and mitigating them with the least intensive analysis method. However, if the analysis results are marginal, then full simulation of the traffic signal system including the light rail line is warranted. The recommended programs for such evaluation are TRANSYT-7F for simpler problems and Traf-NETSIM for complex problems and analysis of system variances.



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APPENDIX

A derivation of the maximum back of queue assuming a constant vehicle arrival rate and Greenshields queue discharge model.

Starting with similar triangles

$$q/1 = Q/(r + 14.2 + t)$$

where

$q/1$ = vehicle arrival rate per second

Q = maximum back of queue

r = effective crossing blockage time or effective traffic signal red time

t = time for which vehicles discharge at maximum saturation flow

Solving for t

$$Q = (q/1)(r + 14.2 + t) = ((5/14.2) \times (14.2)) + (1/2.1)t$$

$$q(r) + 14.2(q) + q(t) = 5 + t/2.1$$

$$q(r) + 14.2(q) - 5 = t/2.1 - q(t)$$

$$q(r) + 14.2(q) - 5 = t(1/2.1 - q)$$

$$(Q(r) + 14.2(q) - 5)/(1/2.1 - q) = t$$

Solving for Q

$$Q = q(r + 14.2 + t)$$

$$t = (q(r) + 14.2(q) - 5)/(1/2.1 - q)$$

$$Q = q(r + 14.2 + (q(r) + 14.2(q) - 5)/(1/2.1 - q))$$

$$Q = q(r) + 14.2(q) + (q^2(r) + 14.2(q^2) - 5(q))/(1/2.1 - q)$$

