# Development of a Dynamic Transit Signal Priority Strategy

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## Abstract

Transit Signal Priority (TSP) is a popular strategy used to enhance the performance of transit systems by modifying the signal control logic to give transit vehicles priority at signalized intersections. Conventional TSP strategies used in most cities have been shown to offer significant benefits in reducing the delays of transit vehicles. However, there have been concerns about some shortcomings of conventional TSP strategies which limited their applications. The main concern is the potential negative impact on cross street traffic. Another concern is the static nature of conventional TSP strategies and the lack of responsiveness to real-time traffic and transit conditions. This paper describes the development and evaluation of a dynamic TSP control system which has the ability to provide signal priority in response to real-time traffic and transit conditions. The dynamic TSP system consists of three main components: a virtual detection system, a dynamic arrival prediction model, and a dynamic TSP algorithm. Two case studies are presented to test and compare the dynamic and the conventional TSP systems. In the first case study, a hypothetical intersection is simulated, while the second case study involves simulating a proposed Light Rail Transit (LRT) line. For both case studies, a virtual detection system was developed in VISSIM, along with a linear travel time arrival prediction model. Finally, a dynamic TSP algorithm was developed to determine what TSP strategy to use and when to apply it. The results showed that the dynamic TSP system reduced the total delay of transit vehicles and outperformed the conventional TSP system in terms of reducing the transit trip travel time.

## INTRODUCTION

Transit Management Strategies have become a necessity rather than an option. Faced with the increase in transit demand and the fixed capacity of the existing infrastructure, urban planners and traffic engineers are developing and improving transit facilities and movements. Transit Signal Priority (TSP) has become one of the most popular ITS solutions. With TSP, priority in the traffic network is awarded to transit vehicles rather than passenger vehicles.

TSP has been widely used in many cities in North America, Europe, and Asia. Conventional TSP strategies used in most of these cities have been shown to offer significant benefits in reducing the delays of transit vehicles. However, there have been concerns about some shortcomings of conventional TSP strategies which limited their applications. The main concern is the potential negative impact on cross street traffic. Another concern is the static nature of conventional TSP strategies since they assume a fixed arrival time for the detected transit vehicles. A third concern is the lack of responsiveness to real-time traffic and transit conditions.

This research attempts to overcome the shortcomings of the conventional TSP systems by developing a “Dynamic” transit signal priority system. The proposed DTSP system is composed of three components; an Automatic Vehicle Location (AVL) detection system, a transit arrival prediction model, and a priority strategy selection algorithm. Two case studies are presented to test and compare these algorithms. The first case study uses a simulated hypothetical four-legged intersection (*1*) while in the second case study a proposed Light Rail Transit (LRT) corridor in British Columbia is simulated. VISSIM was used in the simulation of the two case studies.

## PREVIOUS WORK

At a signal, priority can be awarded to a transit vehicle in different ways and methods. Priority concepts are differentiated by how, when, and where transit signal priority is applied. Several concepts were described in Chada and Newland (*2*), including: active and passive priorities, direct and indirect priorities, and conditional and unconditional priorities. They also described several priority design criteria. These TSP design criteria were based on various parameters such as transit vehicle’s delay, time headway, occupancy, location in queue, and the time since the last priority was provided.

Several priority strategies and techniques were developed through a number of case studies and projects carried out in different cities in North America. Baker et al. (*3*), listed some of these strategies which included: *Green Extension*, *Red Truncation*, *Phase Splitting, Cycle Length Reduction*, *Transit Coordination*, *Queue Jumps*, *Phase Insertion*, and *Phase Rotation*.

Because of the importance of real-time information dissemination to transit users and planners, the development of transit arrival prediction models became an active research area.

Transit arrival prediction models are also important for the application of advanced transit control operations such as dynamic TSP. Accuracy is the main issue when applying arrival prediction models in TSP strategies.

Liu et al. (*4*), attempted to integrate adaptive signal control techniques with advanced transit signal priority techniques. The priority awarded to a transit vehicle would be dependent on a weighting factor given to each transit priority call. A bus with priority would be converted into a relevant number of passenger vehicles using the weighting factor. The weighting factor was determined using the traffic demand and queuing conditions of every approach at an intersection and on the lateness of the transit vehicle. The computed weighting factor would be used to recalculate the signal timings and splits keeping into consideration the signal’s parameters such as minimum and maximum greens, permissive start and end times, and force-off green times.

Lee et al. (*5*), used online microsimulation-based arrival prediction models in developing dynamic TSP systems. The developed method consisted of two major components: an online microsimulation travel time prediction model and a priority operation model. When a transit vehicle is detected, the prediction model is activated to retrieve signal timing information and traffic data from the upstream and the downstream sensors. The developed prediction model was validated using PARAMICS through comparing the predicted bus travel times to the actual travel times. On the other hand, the priority operation model consisted of a library of six priority plans that would be evaluated by the arrival prediction model. After evaluating the travel time of each priority plan, the most appropriate plan with the least travel time would be selected and sent to the signal controller.

Li et al. (*6*), developed an adaptive transit signal priority system on an actuated signalized corridor. The proposed system attempted to give priority to transit vehicles while minimizing the negative impacts on cross street traffic and pedestrian safety. The system consisted of: a continuous detection system, a priority request system, a signal control algorithm that adjusted signals to provide priority, and communication links between them. AVL systems were used to track transit vehicles. Then an arrival predictor, that used both historic and real-time data, was used to predict bus arrival time. Two TSP solutions were used in this study, green extension and early green. The algorithm was tested through simulation and a field test. Results showed considerable time savings in terms of transit delays, while maintaining an acceptable delay level for the minor traffic.

Zhou et al. (*7*), demonstrated the advantages of queue jumper lanes for TSP strategies. An analytical model was developed to estimate optimal detector locations for intersections integrated with TSP and queue jumper lanes under different bus arrival conditions. VISSIM was used to verify the effectiveness of the proposed analytical method. A wide range of detector locations were simulated under three volume conditions. The results showed that for the three volume levels, the detector locations did not have a significant impact on average intersection delay, while having a significant impact on bus delay. Moreover, the impact on bus delay was much more significant under medium and high volumes.

Muthuswamy et al. (*8*), evaluated a TSP algorithm along a signalized existing arterial using simulation. Real-life traffic volumes and signal timing data of AM and PM peaks were used. A future scenario with a 10% volume increase was also simulated. Signal timing plans were optimized and the effects with and without TSP were analyzed. This research had many findings. Firstly, the results indicated that TSP does not always have adverse results on cross streets. Secondly, TSP showed excessive delays along cross streets at heavily congested intersections. Thirdly, applying TSP with optimized signal timing plans was found to significantly reduce transit and auto travel times. Finally, the authors suggested that TSP can reduce the transit fleet size along some routes.

Currie and Shalaby (*9*), reviewed the experiences of TSP applied to streetcars in Melbourne and Toronto. The study concluded that the future of TSP in Toronto is focusing on wide-area implementation and advancement of TSP algorithms. Melbourne, on the other hand, aims to make priority more conditional on the degree of lateness of trams and on the degree of traffic congestion experienced.

As shown, previous research focused on improving the arrival prediction models, expanding the priority solutions library, and minimizing the impact of the TSP solution on cross streets. This research describes the development and evaluation of a dynamic Transit Signal Priority (TSP) control system which has the ability to provide signal priority in response to real-time traffic and transit conditions. Bus arrival time is defined with its upper and lower boundaries and the implementation of the TSP decision is delayed to minimize the impact on cross street traffic. The development of the algorithm is described in the following sections.

## DTSP ALGORITHM DEVELOPMENT

The focus of this research is to develop a dynamic TSP algorithm that provides transit vehicles with the most suitable transit priority strategy at signalized intersections. This algorithm makes use of an AVL system and a transit arrival prediction model. Two different TSP algorithms were developed; a Classic algorithm, and a Dynamic algorithm. The algorithms are developed in VAP; an optional add-on module of VISSIM for the simulation of programmable signal controls.

### The Classic Algorithm

The classic algorithm was designed to compare the performance of the conventional TSP system and the newly proposed dynamic TSP system. The classic algorithm consists of two components; a detection system and TSP decision scheme. The detection system of the classic TSP system utilizes a check-in detector located 50 meters away from the approach stop line, and a check-out detector placed at the stop line. The general procedure of the classic algorithm is presented in Figure (1). In the conventional TSP system, the decision would be instantly taken once a transit vehicle passes the check-in detector. If no detection occurred, the algorithm would run the normal signal settings. The TSP decision scheme incorporated two TSP strategies (*10*):

- Green Extension: If the bus checks in during the bus-approach green phase, extension of the green time is applied. The green phase for the bus would be extended until either the bus checks out or when the maximum green extension of 14 seconds is reached, whichever comes first. Beyond the 14-second green extension, the green phase of the bus-approach phase would end. To achieve offset recovery for coordinated signals, the succeeding green phase of the cross street will be reduced with a time interval equal to the extension.
- Red truncation (or Early Green): If the signal phase is yellow or red when the bus checks in, the red phase will be truncated with a time interval equal to the maximum extension, taking into consideration flash don't walk (FDW) time and a 3-second minimum walk time of the pedestrian phase (conflicting to the TSP-eligible bus approaches). To achieve offset recovery for coordinated signals, the green phase will be extended with a time interval equal to the maximum extension.

## The Dynamic Algorithm

The general procedure of the dynamic algorithm is presented in Figure (2). As shown in the figure, the algorithm is composed of seven major sequential steps. The next subsections describe these steps in detail.

### *1) Transit Vehicle Detection*

Unlike the conventional TSP system which is composed of fixed check-in and check-out detectors, the dynamic TSP system uses AVL for the dynamic detection of transit vehicles. In VISSIM, the only way to model the AVL detection system is a distance-step detection system since VISSIM does not have the option of continuous detection of a certain vehicle. The AVL system was modeled as a group of detectors that are located 10 meters away from each other. The length of the detectors was taken as zero so that the detectors would act as a point detector. As the front wheels of the transit vehicle passes over a detector, a single impulse would be sent to the signal controller.

### *2) Arrival Time Prediction*

In this step, linear models were used to predict transit vehicles arrival times. As well, lower and upper boundaries of the arrival time were defined to determine the arrival scenarios in a later stage. The time length between the predicted arrival time and any of its boundaries was defined as the *boundary length*. The boundary length is one standard deviation from the arrival time. The variance of a linear prediction model can be computed as shown in Equation (1). This equation was used in the algorithm to calculate the variance of the prediction models (*11*).

$$Var = s_d{}^2\left(1+\frac{1}{n}\right)+s_{a1}{}^2\left(x_1 i-\overline{x}_1\right)^2+.....+s_{an}{}^2\left(x_n i-\overline{x}_n\right)^2 \tag{1}$$

$Var$ = variance of the prediction model
$s_d$ = standard error in y (the predicted dependent value)

$s_a$ = standard error of an independent variable
$n$ = number of independent variables in the model
$x_i$ = value of the independent variable
$\overline{x}$ = mean value of the independent variable

In some cases, the arrival prediction models may show bad fit to the data. Hence, refinements should be applied to improve the predictions of these models. Two types of refinements can be used; Empirical Bayes (EB) and Kalman Filtering (KF). In the EB refinement, the travel time of the previous bus is retrieved and used to enhance the model's travel time prediction. This can be mathematically expressed as:

$$P_{Bayes} = \alpha P_{Model} + \left(1-\alpha\right) P_{Previous} \tag{2}$$

Where:

$$\alpha = \frac{1}{1+\left(\frac{Var_{Model}}{P_{Model}}\right)} \tag{3}$$

In the KF refinement, the arrival time prediction is calculated using the arrival time and its variance from the prediction model, and the average travel time and variance of all previous simulated busses. This is shown by Equation (4).

$$P_{Kalman} = \frac{Var_{Previous}}{Var_{Model} + Var_{Previous}} P_{Model} + \frac{Var_{Model}}{Var_{Model} + Var_{Previous}} P_{Previous} \tag{4}$$

### *3) Arrival Time Allocation*

After predicting the arrival time and the lower and upper boundaries, the locations of the arrival time and its boundaries within the cycle were determined. The arrival time allocation was carried out as follows:

a. The arrival time, in seconds, was added to the current cycle second.
b. The number of cycles left until arrival (N), was calculated.
c. The location of the arrival time within the cycle was determined by subtracting the length of N cycles from the sum of the arrival and current times.
d. The same procedure was repeated for the estimated travel time lower and upper boundaries.

### *4) Signal Phase Determination*

In VAP a signal phase is defined using three parameters; GE (Green End), YE (Yellow End), and RE (Red End) (*12*). In a cycle, a signal phase can be arranged in one of three scenarios as shown in Figure (3a). Knowing the three parameters GE, YE, and RE the phase scenario was determined for both the arrival time and its boundaries.

### *5) Arrival Scenario Determination*

After knowing the signal phase of the arrival time and its boundaries, the corresponding arrival scenario was determined. As shown in Figure (3b), seven different arrival scenarios were defined:

- SCENARIO 1: A scenario where the predicted arrival and its upper boundary are in the green phase, while the lower boundary is in the preceding red phase.
- SCENARIO 2: A scenario where the predicted arrival and its lower and upper boundaries are all in the green phase.
- SCENARIO 3: A scenario where the predicted arrival and its lower boundary are in the green phase, while the upper boundary is in the succeeding yellow or red phase.
- SCENARIO 4: A scenario where the predicted arrival is in the yellow phase.
- SCENARIO 5: A scenario where the predicted arrival and its upper boundary are in the red phase, while the lower boundary is in the preceding yellow or green phase.
- SCENARIO 6: A scenario where the predicted arrival and its lower and upper boundaries are all located in the red phase.
- SCENARIO 7: A scenario where the predicted arrival and its lower boundary are in the red phase, while the upper boundary is in the succeeding green phase.

### *6) TSP Solutions*

The type of selected solution or TSP strategy was based on the determined arrival scenario. In this research, three TSP solutions were used:

- SOLUTION 1: This solution is based on the Green Extension Strategy. In this strategy, a green extension will be given to the green phase until the bus checks out the stop line or the maximum extension is reached. Offset recovery is applied in this solution where the succeeding opposing green phase will be reduced with a time interval equal to the extension.
- SOLUTION 2: This solution is based on the Red Truncation Strategy. In this strategy, the red phase will be truncated earlier so that when the bus arrives, the signal will be green. Offset recovery is also applied in this solution where the green phase will be elongated with a time interval equal to the red truncation.
- SOLUTION 3: This solution is based on the Cycle Extension Strategy. In this strategy, the cycle will be extended to have a length of one and half of the normal cycle length in order to make sure that the transit vehicle will arrive at a green phase and in order to retain signal coordination. The solution will be executed for two cycles, replacing three cycles of normal cycle length, then the cycle will be reduced again to its normal length.

The Cycle Extension Strategy has been presented theoretically in many papers. However, its application in real-life projects is rare because of its impact on cross street traffic. To study the impact of this particular strategy, two solutions were applied to SCENARIO 6. The first solution is red truncation and the second is the cycle extension (elongation). In this research, the latter is termed “modified Dynamic TSP” algorithm. In order to understand the way that different solutions work with the arrival scenarios, Figure (4) illustrates the solutions of different scenarios for a period of three normal cycle lengths.

### *7) Taking the Decision*

The time at which the decision is taken is one of the most important and dynamic components of the developed algorithm. After running all the preceding steps and determining the most suitable TSP solution, the algorithm checks whether to apply the TSP solution or wait for some more time. If the decision is to wait, all the preceding steps would be repeated again to check whether the previously determined arrival scenario and TSP solution would still be valid. This component of the dynamic algorithm tries to choose the optimum TSP solution taking into consideration any traffic changes that might cause changes in the arrival scenario. When to take the decision is based on the arrival scenario and on the nature of the selected TSP solution. The developed decision time limits for the seven arrival scenarios are listed in Table (1) and illustrated in Figure (5). The dynamic algorithm runs the normal signal settings until a decision is taken. When a decision is taken, none of the previous steps will be executed, except for detection, until the solution ends and offset recovery is achieved. When the next bus arrives, the algorithm will be ready to grant it the priority it needs.

## CASE STUDIES

### Case Study (1): A Hypothetical Intersection

In the first case study, the Classic and the Dynamic TSP algorithms were compared. A variation of the Dynamic TSP algorithm was also tested to incorporate the cycle extension solution for SCENARIO 6 as described earlier. This variation is termed “modified Dynamic TSP” algorithm. A four-legged hypothetical intersection was modeled using VISSIM to test and compare the TSP algorithms. Each intersection approach consists of two through lanes of 3.5 meters width. One transit line was modeled with a transit stop located upstream of the west bound. The bus dwelling time was defined as a normal distribution with a mean of 15 seconds and a standard deviation of 3 seconds (*13*). A two-phase signal was used to model the primary signal logic. Synchro was used to obtain the cycle length and green splits.

### The Arrival Prediction Model

An accurate arrival prediction model is needed to test the performance of the proposed TSP strategies. A linear regression model was developed using simulation data from the hypothetical intersection. As well, the same intersection was used to test the proposed TSP strategies. The simulation data included distance, dwelling time, and travel time. Three simulation runs were executed for three different exposure levels (750, 1000, 1200 veh/hr). An exposure level refers to the total approach traffic volume with 20% left, 65% through, and 15% right. Travel time measuring points were located every 100 meters for 800 meters. In each simulation run, travel time measurements were collected for four different busses. In total, 96 data points were used for model development. The model included two independent variables; DISTANCE and DWELL. Where DISTANCE is defined as the distance traveled by the transit vehicle to the intersection (meters), while DWELL is defined as the dwelling time of the transit vehicle at a stop (seconds). The developed model is shown in Table (2).

All model parameters were significant at the 95% confidence level. Moreover, the model showed very good fit to the data with $R^2 = 0.99$. This was, to some extent, expected since the four transit vehicles run through the same environment and traffic conditions. As the model showed good fit to the data, the EB and KF refinements were not needed. However, these refinements can be useful in more dynamic situations where an arrival prediction model does not provide such accurate prediction.

## Results of Case Study (1)

For each of the three algorithms, five different simulation runs were completed with various seed values for two different exposure levels (750 and 1000 veh/hr). In total, 30 simulation runs were executed (3 algorithms, 5 seeds, and 2 volume levels). The highest and the lowest delays for each of the five runs were discarded and the average of the remaining three runs was computed. The simulation period was set to 2 hours (7200 seconds). In this period, 40 busses crossed the intersection. Comparisons between the algorithms were based on the total delay of all buses at the intersection. Table (3) shows the sum of delay of all busses, the average delay, and the delay standard deviation for each algorithm. Generally, the developed Dynamic algorithm outperformed the Classic algorithm. The Dynamic algorithm outperformed the modified Dynamic algorithm at the traffic flow level of 750 veh/hr. However, at the higher traffic flow level of 1000 veh/hr, the modified Dynamic algorithm outperformed the Dynamic one. This supports the hypothesis that some TSP solutions could be more beneficial than others according to traffic flow level.

## Case Study (2): The Evergreen LRT Line

In case study (2), a proposed LRT line called the Evergreen line was simulated in VISSIM and used to compare the Classic and the Dynamic TSP algorithms. The Evergreen Line is to be completed by 2009 and will link neighborhoods in Greater Vancouver Regional District (GVRD), as well as connecting with the existing rapid transit system (Millennium Line SkyTrain, West Coast Express) and major bus exchanges (Figure 6). The Evergreen line is a surface-based line with its own right of way. Accordingly, there will be at-grade crossings at 17 signalized intersections on the corridor. Synchro was used to optimize cycle length and offsets along the corridor. Real-life traffic volumes of 2003 PM peak were used. The Evergreen line was chosen for this research for two reasons. Firstly, the variance in arrival time would be minimal as the line has its own right of way. Secondly, there has been strong interest in utilizing TSP strategies to give priority to the proposed line while limiting the impacts on the cross streets. Giving priority to the train at signalized intersections can significantly reduce the trip travel time and improve the scheduling reliability. The following operational characteristics were assumed for the LRT vehicles in this study:

- Vehicle Length (2 vehicle/train): 29.3m
- Passenger Capacity: 340 person/train
- Headway: 3.0 minutes
- Vehicle Acceleration: 1.0 m/s$_2$
- Vehicle Deceleration: -1.0 m/s$_2$
- Maximum Speed: 50.0 kph

- Dwelling Time Distribution: Normal Dist. (20.0±2.0 sec)

## Results of Case Study (2)

A linear arrival prediction model was developed and used to test the TSP algorithms. the model development is presented in detail in Fam (*14*). Again, the model showed very good fit and there was no need for further refinements for the arrival travel time prediction. Two Measures of Effectiveness (MOE) were used to compare the TSP algorithms; LRT total travel time, and cross street delays. Three different situations were compared:

- Situation 1 (No TSP): LRT line operating without any TSP (new signal timing plans necessary to account for conversion of permissive left turns in existing condition to protected left turns).
- Situation 2 (Classic TSP): LRT line operating with Classic TSP at all at-grade intersections.
- Situation 3 (Dynamic TSP): LRT line operating with Dynamic TSP at all at-grade intersections.

Five runs were executed to collect the total trip travel time for each of the three situations totaling in 15 simulation runs. Similar to case study (1), the highest and the lowest travel times for each situation were discarded and the average of the remaining three runs was computed. Table (4) shows the average travel time of the three runs in each direction. The results show that the dynamic TSP strategy reduced LRT travel times by 1.6 minutes in the EB direction, and by 1.4 minutes in the WB direction. The travel time savings with the dynamic TSP strategy were greater than with the Classic TSP. It should be noted that the benefits of the dynamic TSP varied across each of the 17 at-grade intersections where TSP was applied. The travel time reductions were more evident at intersections with higher traffic volumes as a result of lower intersection delays. Therefore, 3 of the 17 intersections experienced 33% of the total travel time reductions.

Cross street delays were computed at all at-grade intersections where the TSP was applied to assess the impacts of using TSP strategies. The delays were averaged for all vehicles on cross street approaches and the results are summarized in Table (5). The results suggest that TSP strategies provide priority to the LRT through movement without significantly penalizing the cross street traffic. Cross streets maintained the same delay levels at all intersections with the inclusion of TSP. Compared to the no-TSP situation, the Dynamic TSP provided lower or at least equal delays at 13 intersections out of the 17. Moreover, In 15 cases the Dynamic TSP showed lower or at least equal delays than the Classic TSP.

## SUMMARY

In this research, a Dynamic TSP system was proposed to replace the Conventional TSP system used in many cities. Microsimulation was employed to test and compare the performance of Conventional and Dynamic TSP algorithms on a hypothetical intersection and a proposed LRT corridor. The Dynamic algorithm used an AVL system to collect bus related information. Using an arrival prediction model, the algorithm recursively checks the predicted arrival time of the bus until it reaches a time limit when a decision has to be taken. Based on the arrival scenario of the bus, an appropriate TSP solution is selected and applied to the signal. The results showed that the Dynamic TSP algorithm outperformed the Conventional TSP one in the two case studies of the research.

A number of research ideas can be further investigated to improve the developed Dynamic TSP system. The dynamic TSP algorithm can be enhanced by adding a larger library of TSP solutions or some newly defined scenarios. In addition, the algorithm can comprise more flexible and effective offset recovery and signal compensation strategies. Finally, a more advanced algorithm can be developed to handle TSP for networks rather than a single intersection or an arterial. In real-life applications of high-frequency transit lines similar to the one used in this study, bunching is a major issue. TSP systems for such contexts have to explicitly include strategies to deal with 2 transit vehicles arriving very close to each other. Also, any practical TSP system should also deal appropriately with 2 transit vehicles arriving at the intersection from two opposite approaches along the same corridor. All these issues will be considered for future investigation.

## REFERENCES

1. Ekeila, W. Dynamic Transit Signal Priority. Unpublished Master of Applied Science, University of British Columbia, 2006.
2. Chada, S., and R. Newland. Effectiveness of Bus Signal Priority. National Center For Transit Research, University of South Florida, USA, 2002.
3. Baker, R. J., J. J. Dale, and L. Head. An Overview of Transit Signal Priority. Prepared by the Advanced Traffic Management System (ATMS) and Advanced Public Transportation System (APTS) Committees of the Intelligent Transportation Society of America (ITS America), Washington, D.C., 2002, revised and updated 2004.
4. Liu, H., A. Skabardonis, and W. Zhang. A Dynamic Model for Adaptive Bus Signal Priority. Presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C, 2003.
5. Lee, J., A. Shalaby, J. Greenough, M. Bowie, and S. Hung. Advanced Transit Signal Priority Control Using On-line Micro-simulation-Based Transit Prediction Model. Presented at the 84th Annual Meeting of the Transportation Research Board, Washington, D.C, 2005.
6. Li, M., Y. Yin, K. Zhou, W. Zhang, H. Liu, and C. Tan. A Dynamic Model for Adaptive Bus Signal Priority. Presented at the 84th Annual Meeting of the Transportation Research Board, Washington, D.C, 2005.
7. Zhou, G., A. Gan, and X. Zhu. Determination of Optimal Detector Location for Transit Signal Priority with Queue Jumper Lanes. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1978*, TRB, National Research Council, Washington, D.C., 2006, pp. 123–129.
8. Muthuswamy, S., W. R. McShane, and J. R. Daniel. Evaluation of Transit Signal Priority and Optimal Signal Timing Plans in Transit and Traffic Operations. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2034*, TRB, National Research Council, Washington, D.C., 2007, pp. 92–102.
9. Currie, G., and A. Shalaby. Active Transit Signal Priority for Streetcars –Experience in Melbourne and Toronto. Presented at the 87th Annual Meeting of the Transportation Research Board, Washington, D.C, 2008.
10. Ngan, V., T. Sayed, and A. Abdelfatah. Impacts of Various Traffic Parameters on Transit Signal Priority Effectiveness. *Journal of Public Transportation*, Vol. 7, No. 3, 2004, pp. 71-93.
11. Sayed, T. and Zein, S. “*Traffic Conflict Standards for Intersections*”. Transportation Planning and Technology, Vol. 22, pp. 309-323, 1998.
12. VISSIM 4.3 Manual, PTV, Germany, 2007.
13. Ekeila, W. Vancouver’s Streetcar Microsimulation Report. University of British Columbia & City of Vancouver, BC, Canada, 2005.
14. Fam, J. Application of Dynamic Transit Signal Priority to the Evergreen LRT Line. Unpublished M.Eng. report, University of British Columbia, Canada, 2006.

## LIST OF TABLES

## LIST OF FIGURES

**TABLE 1 Time Limits of the Seven Arrival Scenarios**

| Scenario | Decision Time Limits |
|---|---|
| ***Scenario 1*** | At the start of the preceding red phase |
| ***Scenario 2*** | N / A |
| ***Scenario 3*** | At the start of the current green phase |
| ***Scenario 4*** | At the start of the preceding green phase |
| ***Scenario 5*** | At the start of the preceding green phase |
| ***Scenario 6 (SOLUTION 3)*** | At the start of the second preceding green phase |
| ***Scenario 6 (SOLUTION 1)*** | At the start of the current red phase |
| ***Scenario 7*** | At the start of the current red phase |

**TABLE 2 The Simulation-based Linear Prediction Model for Case Study (1)**

| | $R^2$ | Variable | Coefficient |
|---|---|---|---|
| **Simulation Based Linear Prediction Model** | 0.99 | DWELL | 1.479 |
| | | DISTANCE | 0.135 |
| | | CONSTANT | 2.274 |

**TABLE 3 Bus Delays of Case Study (1)**

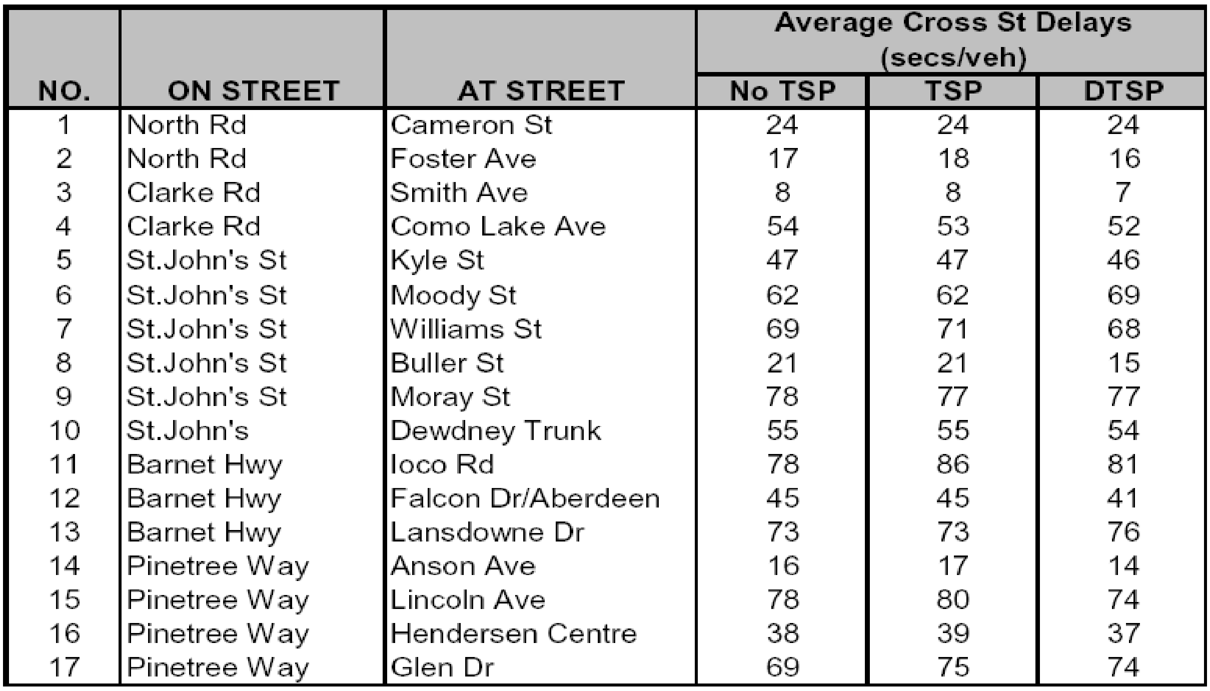
| *Bus Delay* | *Exposure Level (Veh./hr.)* | *Classic* | *Dynamic* | *Modified Dynamic* |
|---|---|---|---|---|
| **SUM*** | 750 | 214.4 | 141.2 | 178.1 |
| **AVERAGE** | | 5.4 | 3.5 | 4.5 |
| **STD** | | 7.0 | 3.8 | 5.9 |
| **SUM** | 1000 | 232.7 | 229.3 | 203.1 |
| **AVERAGE** | | 5.8 | 5.7 | 5.1 |
| **STD** | | 6.9 | 5.5 | 5.8 |

**For 40 buses*

**TABLE 4 Total Trip Travel Time of the Evergreen Line (minutes)**

| Direction | *No TSP* | *Classic* | *Dynamic* |
|---|---|---|---|
| **EB** | 23.3 | 22.9 | 21.7 |
| **WB** | 22.9 | 22.2 | 21.5 |

**TABLE 5 Cross Street Delays of the 17 Intersections of the Evergreen Line (seconds)**



| NO. | ON STREET | AT STREET | Average Cross St Delays (secs/veh) No TSP | TSP | DTSP |
|---|---|---|---|---|---|
| 1 | North Rd | Cameron St | 24 | 24 | 24 |
| 2 | North Rd | Foster Ave | 17 | 18 | 16 |
| 3 | Clarke Rd | Smith Ave | 8 | 8 | 7 |
| 4 | Clarke Rd | Como Lake Ave | 54 | 53 | 52 |
| 5 | St.John's St | Kyle St | 47 | 47 | 46 |
| 6 | St.John's St | Moody St | 62 | 62 | 69 |
| 7 | St.John's St | Williams St | 69 | 71 | 68 |
| 8 | St.John's St | Buller St | 21 | 21 | 15 |
| 9 | St.John's St | Moray St | 78 | 77 | 77 |
| 10 | St.John's | Dewdney Trunk | 55 | 55 | 54 |
| 11 | Barnet Hwy | Ioco Rd | 78 | 86 | 81 |
| 12 | Barnet Hwy | Falcon Dr/Aberdeen | 45 | 45 | 41 |
| 13 | Barnet Hwy | Lansdowne Dr | 73 | 73 | 76 |
| 14 | Pinetree Way | Anson Ave | 16 | 17 | 14 |
| 15 | Pinetree Way | Lincoln Ave | 78 | 80 | 74 |
| 16 | Pinetree Way | Hendersen Centre | 38 | 39 | 37 |
| 17 | Pinetree Way | Glen Dr | 69 | 75 | 74 |

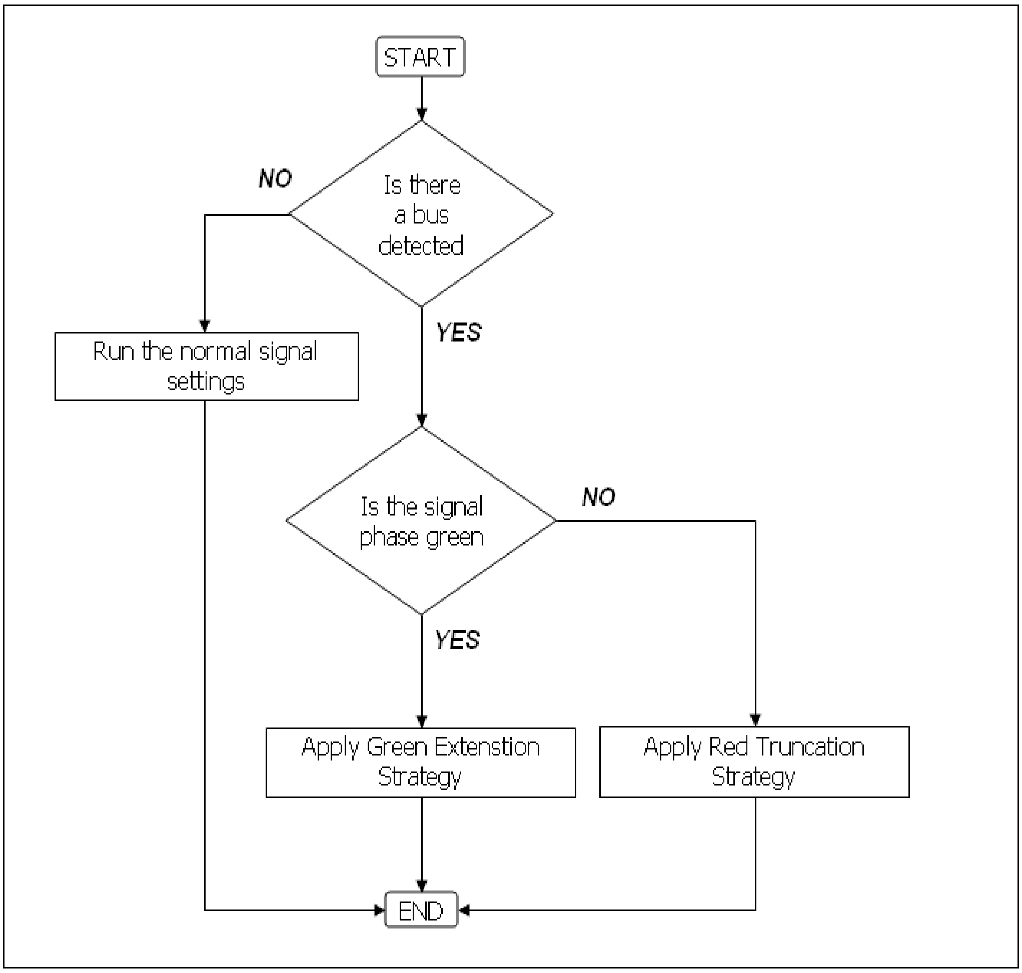


**FIGURE 1** **The Conventional TSP Flowchart**

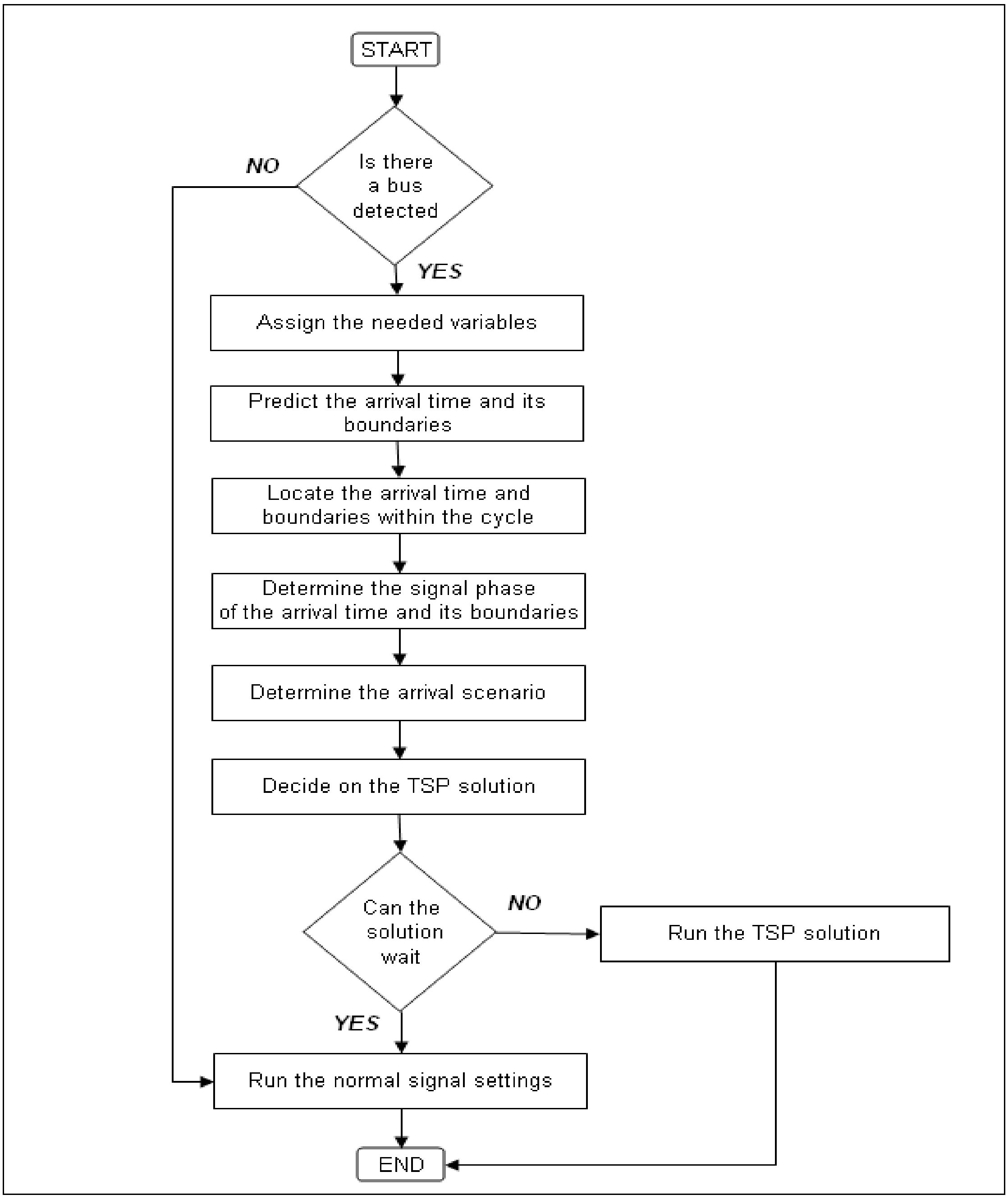


**FIGURE 2** **The Dynamic TSP Flowchart**

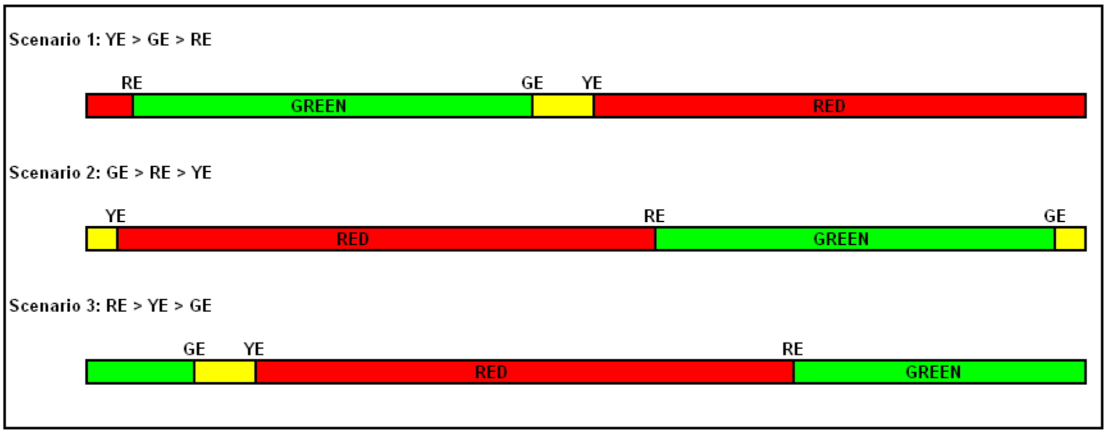


**FIGURE 3a** **Phase Scenarios**

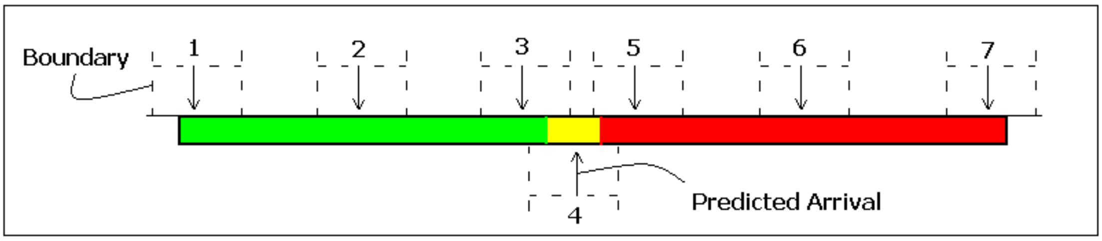


FIGURE 3b Arrival Scenarios

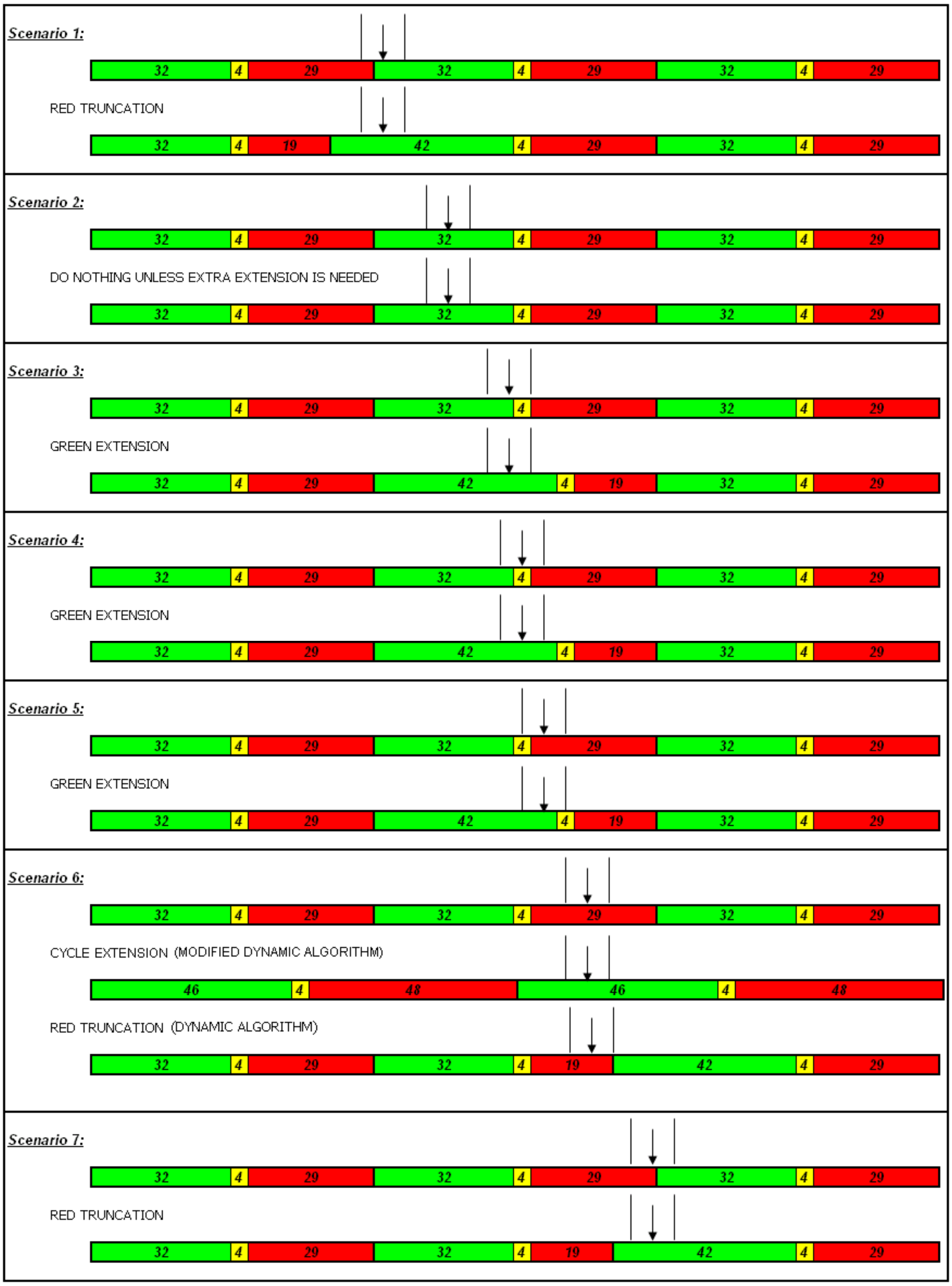


FIGURE 4 Illustrations of TSP Solutions

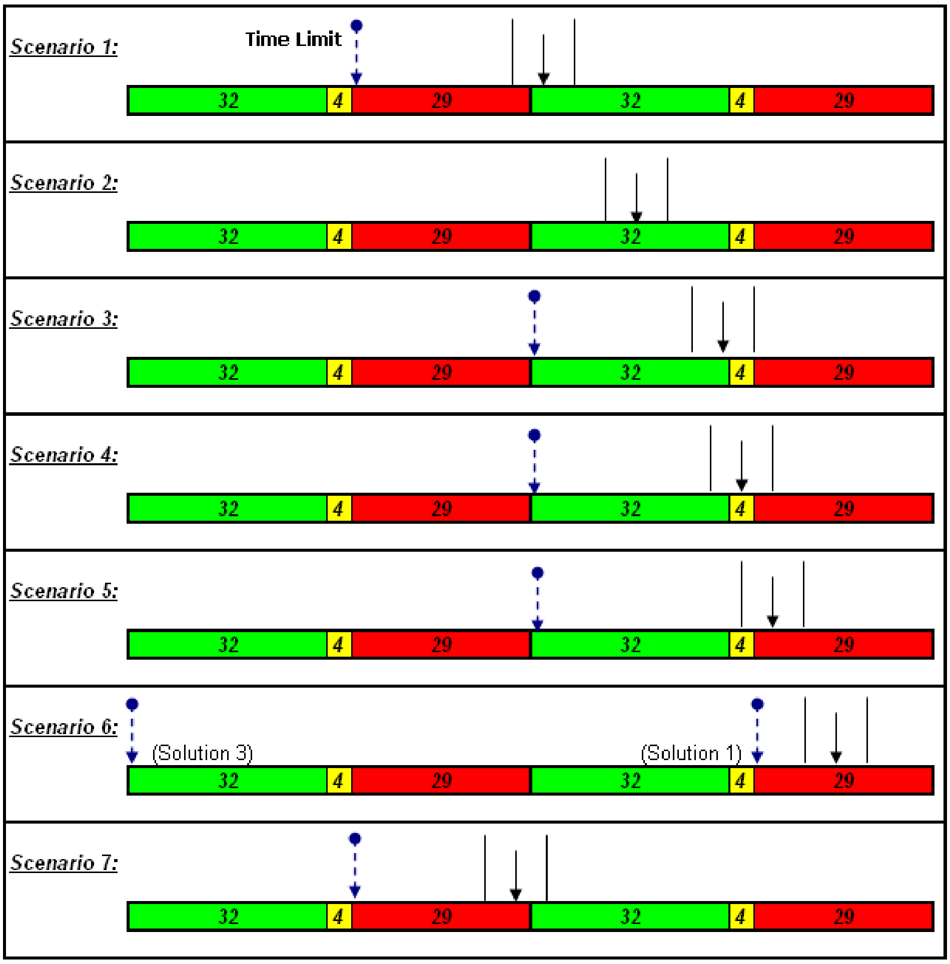


FIGURE 5 Time Limits of the Seven Arrival Scenarios

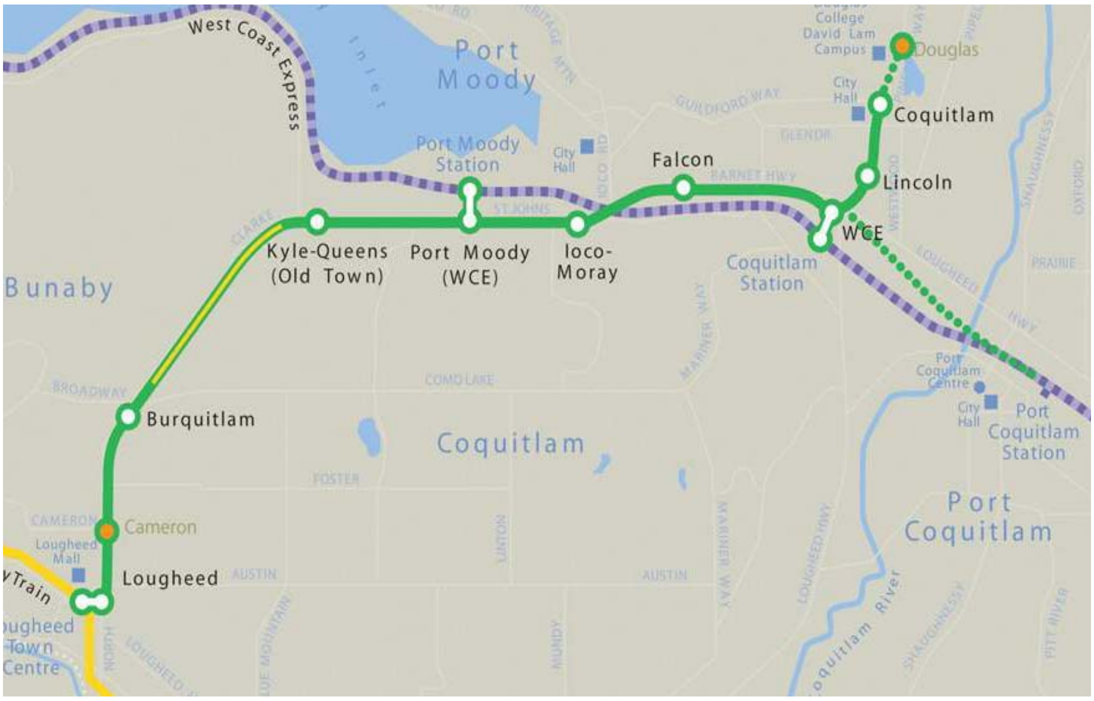


FIGURE 6 Evergreen LRT Line Alignment (*14*)