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# Transit ITS Simulator (TRANS-ITS): Design Document

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# TRANSIT ITS SIMULATOR
# (TRAN-ITS)
# DESIGN DOCUMENT

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# ABSTRACT

This report describes a simulation model developed to evaluate the impact of using Intelligent Transportation Systems (ITS), such as Global Positioning Systems (GPS) for bus tracking, on controlling buses in wide-area transit networks. Control strategies with ITS will be compared against those without ITS (i.e., they do not rely on communication or tracking). The model is developed using a general-purpose simulation language, AweSim (Pritsker, 1997). The simulation model is generic and independent **of** any dedicated transit network. The model has high flexibility and can be used to simulate different kinds of transit networks with varying numbers of bus lines and different travel patterns. The user has the flexibility to input the appropriate control strategy at each bus stop. With this approach an identical replica of an actual system can be simulated. **A** set of experiments is being developed to analyze the use **of** ITS on several performance metrics, including average bus arrival and departure lateness, average passenger trip time, and average total passenger waiting time.

Keywords: GPS, Productivity, Simulation, Tracking, Transit

# EXECUTIVE SUMMARY

Recently, bus transit service providers have begun to adopt Intelligent Transportation Systems (ITS) technologies such as Global Positioning Systems (GPS), Mobile Data Terminals, and Electronic Fare boxes. GPS systems are particularly useful for vehicle tracking and mobile data terminals may be used for passenger counting. These systems taken together have the potential to reduce the cost of providing transportation services through the execution of real-time control strategies, performance monitoring systems and data collection to support service realignment.

The objective of this project, "Efficient Transit Service Through the Application of ITS" (PATH MOU 280), is to investigate the application of ITS technologies to improve the overall efficiency and productivity of transit operations. The perspective will be to minimize the cost of achieving a desired level of service or, alternatively, maximizing the service quality within a given budget. Metrics to be investigated include fleet size and service frequency, passenger waiting and travel times, driver hours-of-service, and fare-box collection. The investigation covers field evaluation of the impact of ITS on driver and fleet productivity (documented in a separate working paper) and simulation of transit networks with ITS capabilities. A final report, covering all project elements, will be delivered in the summer of 1998.

As part of this project, bus control strategies using ITS are evaluated against those without ITS. Two levels of ITS are considered: (1) system with centralized tracking and (2) system with information on connecting passengers, as well as centralized tracking. By making use of real-time information such as vehicle location, it is expected that control strategies using ITS have the potential to improve connectivity between origins and destinations while reducing passenger waiting times.

This preliminary report documents the approach used in the development of the simulation model for analyzing the various control strategies. The simulator developed for this study is an expansion of the simulation model developed by Hall et al(1997) to analyze the effectiveness of ITS on scheduling buses at timed transfer terminals. This new simulator considers connectivity of buses at traditional transfer stops as well as at timed transfer terminals. The model has the capability to simulate wide-area transit networks. With this feature, we can study the impact of holding a bus at a particular stop on the waiting time for passengers boarding on subsequent stops. Another major addition to the simulator is the inclusion of passenger entities in the model. In this manner, real-time control strategies taking into account passenger count and waiting times may be considered. Furthermore, including passenger entities permits the explicit modeling of the boarding and debarking process. Hence, the phenomenon of an initial delay in service causing deteriorating service farther down the line due to the increased accumulation of boarding passengers can be studied.

# 1. INTRODUCTION

Intelligent Transportation Systems (ITS) have been investigated **as** a means to improve the quality of service for automobiles, trucks, buses and other modes. ITS also has the potential to reduce the cost of providing transportation services. In the transit industry, Global Positioning Systems (GPS), Mobile Data Terminals, and Electronic Fare Collection may enable providers to improve the efficiency and productivity of drivers and fleets. This would occur through the execution of real-time control strategies, performance monitoring systems and data collection to support service realignment.

With the use of real-time information and bus control, connectivity between origins and destinations may be improved while reducing passenger waiting times. This may enable the transit operator to maintain service levels with a reduced fleet size. Through assessment and improvement of driver productivity, the operator may be able to reduce the cost of meeting its current schedules, largely through reduced overtime charges. Finally, through electronic fare collection, the operator may be able to recover revenue that is lost through incorrect fare payments. Technologies might also have the benefit of reducing boarding times, which would both improve service and reduce operating cost.

The objective of this project is to investigate the application of ITS technologies to improve the overall efficiency and productivity of transit operations. The perspective will be to minimize the cost of achieving a desired level **of** service or, alternatively, maximizing the service quality within a given budget. Metrics to be investigated include fleet size and service frequency, passenger waiting and travel times, driver hours-of-service, and fare-box collection.

One aspect of this study is to evaluate the use of ITS technologies on real-time control of buses. Some real-time control strategies include decisions regarding whether to (1) increase or reduce the travel speed, **(2)** hold or release a bus at a transit center, and **(3)** insert a bus in the schedule. These decisions clearly depend on the planned schedule (e.g., bus headways and scheduled departure times at the bus stops) and real-time status of the transit system such as information on current lateness of the buses, number of passengers on board buses and waiting at the various stops, and forecast arrival times of buses. With ITS it will be possible to relay this information in real-time to the controller.

**A** simulation model of a wide-area transit network is developed to evaluate various real-time control strategies with ITS versus those without ITS. Sample control strategies without **ITS** include hold a bus at a transit stop until all connecting buses have arrived or never hold **a** bus past its scheduled departure time. **A** sample control strategy using ITS is to hold a bus at a transit center if a connecting bus is forecasted to arrive within ***5*** minutes. The control strategies will be evaluated based on several performance metrics, including average bus arrival and departure lateness, average passenger trip time, and average total passenger waiting time

This preliminary report documents the approach used in the development of the simulation model for analyzing ITS effectiveness on overall transit operations. The simulator developed for this study is an expansion of the simulation model developed by Hall et al (1997) to analyze the effectiveness of ITS on scheduling buses at timed transfer terminals. This new simulator considers connectivity of buses at traditional transfer stops as well as at timed transfer terminals. The model has the capability to simulate wide-area transit networks. With this feature, we can study the impact of holding a bus at a particular stop on the waiting time for passengers boarding on subsequent stops. Another major addition to the simulator is the inclusion of passenger entities in the model. In this manner, real-time control strategies taking into account passenger count and waiting times may be considered. Furthermore, including passenger entities permits the explicit modeling of the boarding and debarking process. Hence, the phenomenon of an initial delay in service causing deteriorating service farther down the line due to the increased accumulation of boarding passengers can be studied.

The remainder of this report is divided into 5 sections. We first review the relevant literature in transit modeling. Second, the real-time control strategies with and without ITS are presented. Third, we describe how vehicle and passenger forecasting is implemented in the model. Fourth, the simulation methodology is presented as well as the inputs and outputs of the model. The final section provides conclusions.

## 2. RELATED RESEARCH IN PROBLEM AREA

### Transit Modeling

There is a considerable literature on analytical and simulation-based approaches for optimizing public transportation systems. Most studies minimize a total cost function that has two components: transit firm costs and passenger delay cost. Chang and Schonfeld (1991) develop analytic models to determine headway, fleet size, and route spacing under various assumptions of demand elasticity and time variability for a feeder bus system. Talley (1989) develops square-root equations for determining the optimal frequency of bus service to minimize the transit bus firm's cost and passenger time costs subject to budget constraints. Van Oudheusden and Zhu (1994) develop an integer programming model to determine trip frequency for the Bangkok public transit system assuming inelastic demand. Because of the computational difficulty of solving the integer programming model, the authors present two simple heuristics that performed well to solve the problem. One heuristic is based on a linear program relaxation of the model while the other heuristic is based on rules-of-thumb. Other studies that assume a fixed demand include the work of Wirasinghe (1980), Tsao and Schonfeld (1984), and Kuah and Perl (1988).

Other related literature includes the work in modeling passenger behavior, which may benefit from ITS technologies. Previous work has focused on both transit route selection (often referred to as the transit assignment problem) and predicting passenger waiting times. For the former problem, Spiess and Florian **(1989)** provide an excellent survey of the literature and formulate the transit assignment problem as a linear program. The authors include expected passenger waiting time as well **as** travel time in their model to determine the optimal route. Jayakrishnan, McNally, and Marar **(1995)** develop equations that can be solved recursively to find the probability of selecting a route given random arrivals. Hall **(1983)** develops adaptive route choice rules which respond to dynamic information, and evaluates those rules with traveler experiments and network analysis. Shih, Mahmassani and Baaj **(1996)** develop a **trip** assignment model for three different types of transfer terminals: uncoordinated, coordinated with common headway and coordinated with integer ratio headways for all routes. Lin, Liang, Schonfeld and Larson **(1995)** focus on developing bus dispatching criteria at various stops. A holding and stop skipping criteria is analyzed and optimized based on specified cost functions. They also compare various criteria of interest under headway based and scheduled based controls. The work focuses primarily on a single route, not taking into account transfers and transit centers. The study reveals that tight stop skipping control significantly increases the average wait time, while the most critical decision variable is the holding control parameter.

While much has been written on control of bus schedules, little has been published on the use of ITS technologies to enhance driver/bus productivity. As reported in Benn (1995), bus productivity measures used in the industry focus on the bus line **as** the fundamental unit, and are not real-time based. He also states in his conclusion that ITS will lead to drastic changes in the way bus performance is measured: "AVL will be bringing real time information down to the bus stop level. Bus route evaluation issues will likely include how to select between routes when initially installing the system, what route level standards will determine this, and further, does a wait become more tolerable to an intended passenger when real time information is provided?" As an example of the potential use for tracking data, Henderson and Darapeneni **(1994)** discuss how the New York Transit Authority is using its subway on-time performance data within a multi-variate regression model to assess the causes of delays and develop remedies.

This research differs from the previous work on transit modeling by studying the impact of ITS technologies on the bus control and fleet size determination problems. Control strategies making use of real-time information such as the number of passengers transferring between lines, the bus positions, and the number of passengers waiting at any stop will be analyzed with intent to improve schedule adherence and reduce the fleet size.

## Probability Distributions Models for Delay

We first define several variables that are commonly used in the literature. Lateness is defined as the deviation from the scheduled arrival time at a check point or stop and delay is defined as the deviation from the scheduled travel time over a segment. The relationship between lateness and delay can be expressed as follows:

$$L_k = A_k - S_k \qquad (1)$$

$$D_k = L_k - L_{k-1} \qquad (2)$$

where:

$A_k$ = the actual arrival time of a bus at stop k
$S_k$ = the scheduled arrival time of a bus at stop k
$L_k$ = the lateness of a bus at stop k
$D_k$ = the delay on the bus segment preceding stop k

Based on the above definitions, the actual travel time over the bus segment preceding stop k, $A_k - A_{k-1}$, equals the sum of the scheduled travel time, $S_k - S_{k-1}$, and a random delay, $D_k$. The lateness at stop k, $L_k$, can be interpreted as the cumulative delay of all bus segments preceding stop k,

$$L_k = \sum_{j=1}^{k} D_j.$$

Negative lateness means that a bus arrived early at a stop and negative delay means that a bus traveled faster than scheduled on a particular segment.

Table 1 summarizes probability distributions for the various random variables used in past studies. The work by Abkowitz et al. (1987), Lee and Shonfeld (1991), Hall (1985) and Talley and Becker (1987) can be classified as either delay (travel) or lateness (arrival) since they modeled a single bus stop and under this case the two variables are the same. Most studies prefer to use a skewed distribution such as lognormal or gamma since it is more likely to be behind schedule than ahead. Some authors select the probability distribution based on empirical studies (e.g., Turnquist, **1978;** Talley and Becker, **1987;** Guenthner and Hamat, **1988;** Seneviratne, **1990);** Strathman and Hooper, **1993)** while others based their selection on model simplification (e.g., Andersson and Scalia-Tomba, **1981;** and Hall, **1985).**

## Table 1. Summary of Previous Studies

| Authors | Random Variable | P.D.F |
|---|---|---|
| Turnquist (1978) | Arrival Time | Lognormal |
| Bookbinder and Desilets (1992) | Arrival Time | Truncated Exponential |
| Strathman and Hopper (1993) | Arrival Time | Lognormal |
| Guenthner and Hamat (1988) | Arrival Time | Gamma |
| Abkowitz et al. (1987) | Arrival Time | Normal |
| Lee and Shonfeld (1991) | Arrival Time Travel Time | Normal, Gumbel |
| Hall (1985) | Lateness, Delay | Exponential |
| Hall et al. (1997) | Delay conditioned on present lateness | Normal |
| Talley and Becker (1987) | Lateness, Delay | Exponential |
| Jenkins (1976) | Travel Time | Normal |
| Anderson et al. (1979) | Travel Time | Lognormal |
| Turnquist and Bowman (1980) | Travel Time | Gamma |
| Wirasinghe and Liu (1995) | Travel Time | Gamma |
| Seneviratne (1990) | Travel Time | Normal, Gamma |

Past studies have shown that once a bus with low headway gets delayed, it rarely makes up for the delay due to the bunching of vehicles. In this case, the increase in the number of passengers who board results in higher and higher delay en-route. As was observed by Turnquist **(1978),** $D_k$ and $L_{k-1}$ are positively correlated with a high lateness at a stop resulting in increased delay over the subsequent segment.

Although the above phenomenon is generally true for buses with short headways, it does not always occur on buses with high headway. Unlike short headway lines, passengers tend to consult schedules prior to arriving at stops. Hence, late buses do not board significantly more passengers than on-time buses. Further, since higher headway buses often have slack built into their schedule, there is opportunity to make up for some of the lost time (Hall et al. (1 **997)).** Further, since most transit agencies penalize their driver for being excessively late, drivers have an incentive to catch up to the schedule. Thus the delay in a segment is negatively correlated with the lateness at the start of the segment.

Because of these two phenomena, the delay on a bus line segment can either be negatively or positively correlated with the lateness at the start of the segment, depending in large part on the line headway. The simulation model being developed accounts for both of these phenomena. A positive correlation can be reflected in the simulation of passenger who do not consult a schedule prior to arrival, which results in increased boardings when a bus falls behind schedule on a short headway line. **A** negative correlation can be reflected in the slack built into the schedule. We model this process by first sampling the travel time over a segment from a normal distribution. The travel time is then truncated on the left to impose a limitation on the maximum earliness. The amount of truncation depends on the slack and the lateness of the previous stop **(**$L_{k-1}$**).**

## Probability Distribution Models for Arrival Times of Passengers

Most research in the field of transit reliability has assumed random arrivals of passengers to a stop; see for example Barnett **(1974)** or dePirey **(1974).** Past studies indicate that the there are two categories of passengers who board the bus. Some people are aware of the scheduled arrival while others are not. Those aware of the schedule time their arrival to a stop to coincide with the arrival time of the bus. Unaware passengers come randomly to a stop, thereby having to wait for a longer duration of time. Okrent **(1974)** conducted a study on data collected from the Chicago mass transit system to estimate the manner in which aware passengers select their arrival times to a station. He concluded that a headway of **12** to **13** minutes marks the transition period, where a much greater fraction of people tend to be aware of the schedule. Similar results were found by studies conducted by Jolliffe and Hutchinson **(1975)** and Marguier and Ceder **(1984).** Coslet **(1976)** used utility theory to predict the arrival time of aware passengers. The study conducted by Bowman and Turnquist **(1981)** shows that arrival times of passengers for high headway buses follow a skewed normal distribution, peaking just before the scheduled arrival time and fading steeply beyond it. The study also showed that the variance of the arrival distribution greatly reduces as the reliability of the bus service increases. Bowman and Turnquist (1981) also found that for low headway buses, the arrival times of passengers to a stop are uniformly distributed over the duration of the headway.

In our model, we build on the observations of Bowman and Turnquist (1981). Buses are classified into categories of high and low headway. Two set of passengers are generated for each bus, ones that are aware and the others that are unaware. The fraction of aware passengers is higher for the high headway buses. The arrival time of aware passengers is sampled from a truncated normal distribution with mean being slightly smaller than the scheduled arrival time of the bus. The distribution is truncated on the right to avoid sampling arrival times well beyond the scheduled arrival time and to the left by one headway. The arrival time of unaware passengers is sampled from a uniform distribution, timing their arrivals between two subsequent runs of a bus line.

The arrival time distribution is assumed to be static and independent of the service reliability of the bus lines. However, in the future we plan to implement feedback information concerning the reliability of the bus lines that are dynamically collected over the simulation run and changing the arrival time distributions to reflect the effect of the changed reliability. It is expected that with the implementation of **ITS,** the reliability of bus services would improve, thereby increasing the fraction of aware passengers and reducing the variability of their arrival times.

## 3. BUS HOLDING STRATEGIES

Each bus in the transit network is controlled by some holding strategy when it arrives **to** a stop or checkpoint. The holding strategy depends on the nature of the stop (e.g., transit centers such as a timed transfer stations or uncoordinated stops). To allow for different types of stops in the network, a different holding strategy is defined for each stop in the transit network.

Some of the strategies are only applicable to timed transfer stops. Transit systems have timed transfer terminals where a certain number of buses arrive within the same time window, to facilitate the transfer of passengers from one bus line to another. Control strategies evaluated in the absence of bus tracking are (1) No Hold (2) All Hold and **(3)** Hold for a fixed period of time. However, all three strategies suffer from **the** lack of accurate up to date information on different bus lines. The static and prefixed schedules do not allow for dynamic decision making by the dispatchers. As a result, the efficiency of the system may be lower using control strategies that do not make use of ITS. The advent of **ITS** technology for tracking the buses has changed the scenario. In light of the up to date information, more dynamic decision making is feasible.

We next describe the control strategies that have been implemented as part of the simulation model. A mathematical representation of the holding strategies is included in Appendix A. Each bus stop in the transit network has its own control strategy.

1. Do not hold any bus.
2. Hold a bus, if a connecting bus is scheduled to arrive within a time bucket.
3. Hold a bus for a fixed period of time, if a connecting bus is scheduled to arrive within a time bucket.
4. Forecast the arrival times for different bus lines approaching the stop. Hold if the following conditions are true:
    - Bus has a high headway
    - Forecast arrival time of an approaching bus is within a fixed holding time.
5. Forecast the arrival of different bus lines approaching the stop. Hold a bus if all the following conditions are true for any approaching bus:
    - Bus has a high headway
    - Forecast arrival time of an approaching bus is within a fixed holding time.
    - More than a fixed number of passengers on board the arriving bus who want to transfer to the waiting bus.
6. Forecast the arrival of different bus lines approaching the stop. Hold a bus if all the following conditions are true for any approaching bus:
    - Bus has a high headway
    - Forecast arrival time of an approaching bus is within a fixed holding time.
    - More than a fixed number of passengers on board the arriving bus who want to transfer to the waiting bus.
    - The total waiting time of passengers on board the holding bus due to the extra hold, is less than the cumulative waiting time that the transferring passengers would face as a result of missed connection and having to wait for the subsequent run.

To allow for model flexibility, the user inputs the appropriate strategy for each stop, depending on the headway of the buses and the nature of the transition matrix from one bus line to another. The model also allows the user to specify, if early departure is possible from a stop or not. A standard bus stop with no connections can be simply modeled as a No hold (Strategy 1) with possibility for early departures

## 4. FORECASTING METHODS

Some of the holding strategies require a forecast on bus arrival times and the number of passengers on the bus. We next describe the forecasting methods used in the model when a stop uses a holding strategy that requires ITS.

***Arrival Time Forecast***

In the presence of a bus tracking system, arrival times can be forecasted to any stop. We assume that the forecast is updated each time the bus passes a scheduled stop. The bus sends its forecast to the subsequent stops once on arrival and again at the departure. Since the arrival and the departure times of a bus at a stop may not coincide, the revised forecast at the departure is expected to be different from the ones sent on arrival.

The forecast sent to the subsequent stop is the sum of the current lateness and the expected travel and dwell time to the subsequent stop.

$$F_{i,k,k+1} = L_{i,k} + AT_{i,,k+1} + Dw_{i,k} \qquad (3)$$

where:

| | |
|---|---|
| $F_{i,k,k+1}$: | Forecast arrival time to stop $k+1$ made at stop $k$ for line i |
| $AT_{i,k+1}$ | Expected actual travel time from stop $k$ to stop $k+1$ for line i |
| $L_{i,k}$ | Lateness at stop $k$ for line i |
| $Dw_{i,k}$ | Average boarding and disembarking time at stop $k$ for line **i** |

Forecast arrival times for stops greater than $k+1$ can made by iteratively using Equation (3).

Based on the discussion in Section **2,** the expected actual travel, AT„, **,** can be determined as follows.

$$AT_{i,k} = \max(\gamma_{i,k}\, ST_{i,k}, ST_{i,k} - \max(0, L_{i,k})) \qquad (4)$$

where:

| | |
|---|---|
| $ST_{i,k+1}$ | Expected scheduled travel time to stop $k$ for line i |
| $\gamma_{i,k}$ | Maximum slack from scheduled travel to stop $k$ for line i |

The expected scheduled travel time, $ST_{i,k+1}$, is simply the difference between the scheduled departure times between adjacent stops minus the expected boarding and disembarking time, $Dw_{i,k}$. Note that the expected actual travel time is smaller if the bus is currently late, allowing the bus to travel faster if it is behind in the schedule. The travel time in the model is then sampled from a truncated normal distribution with mean, $AT_{i,k}$. The travel time is truncated on the left to impose a limitation on the maximum earliness. The amount of truncation is given by $\gamma_{i,k}$ ST„„.

***Passenger Forecast***

We also forecast the number of passengers on board the bus when it arrives at each subsequent stop. The forecast is sent on arrival to a stop and again at the time of departure. The expected number of passengers on board depends on the number of connecting buses that the given bus might intersect on its way to a stop. Hence, the forecast on the number of passengers is dependent on the control logic at subsequent stops. For example in case of a no hold strategy, it is likely that there are no transferring passengers, while in case of an all hold strategy, there would certainly be transfers thereby increasing the number of passengers on board. **A** very conservative approach is to forecast the present number on the bus plus the expected number of originating passengers at subsequent stops. However, this approach does not result in accurate predictions, since it does not take into account the passengers who might get off the bus or the extra transferring passengers who might board the bus. Using the control logic at subsequent stops, a more sophisticated approach can be used to predict the expected number of passengers. We describe the approach used in the model next.

$$FP_{i,k+1}=P_{i,k}*C_{i,k}+O_{i,k}+TP_{i,k} \qquad (5)$$

where:

| | |
|---|---|
| $FP_{i,k+1}$ | The forecast number of passengers on bus line i at stop k+1 |
| $C_{i,k}$ | The fraction of continuing passengers on line i at stop **k** |
| $O_{i,k}$ | The number of originating passengers at stop k for line i |
| $TP_{i,k}$ | The number of transferring passengers at stop k to line i |
| $P_{i,k}$ | The number of passenger on board the bus at stop **k** on line i |

There are several different ways to calculate $TP_{ik}$. The following three different methods have been modeled for estimating $TP_{ik}$.

Method I

$$TP_{i,k}=\sum FP_{j,k}*C_{j,i,k}*I^1_{j,i}$$

Method II

$$TP_{i,k}=\sum FP_{j,k}*C_{j,i,k}*I^2_{j,i}$$

Method III

$$TP_{i,k}=\sum FP_{j,k}*C_{j,i,k}*I^3_{j,i}$$

where:

| | |
|---|---|
| $FP_{j,k}$ | The forecast number of passengers on line j to stop k |

| | |
|---|---|
| $C_{j,i,k}$ | The fraction of people transferring from line j to line i at stop **k** |
| $I^1_{j,i,k}$ | Equals 1 if the forecasted arrival time of line **j** is before the scheduled arrival of line i at stop k ($F_{jk}<S_{ik}$) |
| $I^2_{j,i,k}$ | Equals 1 if the forecasted arrival time of line j is before the scheduled arrival of line i at stop k plus some threshold value **($F_{jk}<S_{ik}$+Threshold** value) |
| $I^3_{j,i,k}$ | Equals 1 if the forecasted arrival time of line j is before the forecast arrival of line i at stop k ($F_{jk}<F_{ik}$) |

## 5. SIMULATION MODEL

**A** simulation model of a wide-area transit network is developed to evaluate various real-time control strategies with ITS versus those without ITS. The model is developed using a general-purpose simulation language, AweSim (Pritsker, 1997). The advantage of using a process-oriented language to model bus operations is that a small network model, which has the flexibility to test many different control strategies, can be used to represent detailed bus movement. The simulation model is generic and independent of any dedicated transit network. The model has a high flexibility and can be used to simulate different kinds of transit networks with varying number of bus lines and different travel patterns. The user **has** the flexibility to input the appropriate control strategy at each stop. With this approach **an** identical replica of an actual system can be simulated.

The scheduled arrival times at each major stop for each bus line are input to the model. The scheduled travel time between major stops defines a particular segment along a bus line. The model simulates the movement of a bus on each segment on the line until it finishes its visit to all its scheduled stops. The actual travel time on each segment is sampled fiom a truncated normal distribution with mean AT,,, **as** defined in Equation **(4).** Consistent with the simulation model of Seneviratne (1990) we assume that the number of boarding passengers at each stop is Poisson distributed. The arriving passengers are categorized into aware and unaware passengers. Arrival time is associated with the arriving passengers, using either the normal or uniform distribution, depending on their category. The mean of the normal distribution is slightly before the bus is scheduled to arrival at the stop. The passenger arrival times sampled from the uniform distribution are spread between two subsequent runs of a bus.

The boarding times of the passengers are modeled as a Gamma distribution. Kraft (1977) proposed the usage of a 2-Erlang distribution. Since the Erlang distribution is a special case of the Gamma distribution, a higher degree of modeling flexibility is obtained by using the Gamma distribution. **As an** initial set of parameters, the mean boarding and debarking times are set to 4.2 and 2.1 seconds, as proposed by Koffman (1978).

Debarking and boarding takes place simultaneously at a stop. **A** delay equaling the maximum of the boarding and debarking time is applied on arrival of a bus to a stop.

However, it is possible that new passengers including originating and connecting passengers will arrive after all the debarkings have taken place. Under such a condition, an extra delay equaling the boarding time of the new passengers is applied to the bus if they arrived after the holding time.

The model forecasts bus arrival times and the number of passengers on board for stops that use an ITS based control strategy. The forecast arrival time for a bus to its next stop is the present lateness plus the expected travel time and dwell time. Forecasts to subsequent stops can be iteratively calculated using Equation **(3).** The forecast on the number of passengers is the sum of passengers continuing on the bus plus the expected number of originating and transferring passengers and is iteratively calculated using Equation (5).

The user has the option to specify the method to calculate the expected number of transferring passengers on board the bus. The different methods are described in Section **4.** Appendix B describes the modeling logic and the variables used. 'We next describe the inputs and outputs of the simulation model.

***Inputs to the simulation model***

The network transit system that is simulated is defined and controlled by many user input parameters. For example, the routes are specified by inputting the scheduled departure times of the first run of each bus line at each stop. The scheduled departure times of subsequent runs of the bus are determined by the inputted headway. The model reads all input parameters from data files. The following table summarizes the inputs to the simulation model. In the table, the Index I represents the bus line number and the Index J represents the $j^{th}$ stop in the route.

| **INPUTS** | **Description** |
|---|---|
| NLINE | The number of bus lines in the transit network |
| NSTOP[I] | Number of stops for bus line I |
| AC_STOP[I][J] | The sequence of stop numbers visited by each bus line. |
| **VAR** [I] | Variance of travel time for bus line I. |
| SLACK[I] | Maximum slack built into the schedule for bus line I. |
| HEADWAY[I] | Headway for bus line I |

| | |
|---|---|
| ARRIV_T [I][J] | Scheduled arrival time for bus line I to stop J<br>(array stores values only for the first run of each bus line) |
| DEPAR_T [I][J] | Scheduled departure time for bus line I from stop J<br>(array stores values only for the first run of each bus line) |
| BOARDS[I][J] | The average number of boarding passengers at stop J for bus line I<br>(Poisson Distribution is used to generate the number boarding) |
| T_BOARD & T_DEBARK | Represents the average boarding and debarking time per passenger (Gamma distribution is used to generate the actual boarding and debarking times) |
| AWARE[I][J] | The fraction of people boarding a bus who are aware of the scheduled arrival time of bus line I at stop J |
| TRANS[J][I][K] | Transition matrix of transferring passengers when bus line I arrives to stop J<br>Index K represents the transferring bus line number. K varies from 0 to NLINE where 0 represents the fraction of passengers who want to be dropped off. |
| STOP_D[J] | Control strategy at stop J |
| STOP_ED[I][J] | Binary variable representing whether or not a bus can leave earlier than its scheduled departure time from stop J for line I |
| CAPACITY[I] | Bus capacity for bus line I |
| I_LOAD[I] | Initial load of passengers on bus line I when it enters the transit network |
| WINDOW | To coordinate movement of different bus lines whose scheduled arrival times to a stop do not differ by more than WINDOW |
| MAX_W[J] | Maximum allowable holding time at stop J |
| MAX_P | Threshold value for the number of transferring passengers |
| FORE_P | The technique used for forecasting the passenger count of a bus line to its subsequent stops |
| H_HEADWAY | Bus lines with headway over H_HEADWAY represent the high headway lines |

### ***Outputs of the simulation model***

Passenger performance metrics in the simulation model are (1) total delay and (2) total trip travel time. Equally important criteria for an effective transit system is the schedule adherence of the different bus lines along their respective routes. In light of the above performance indicators, the simulation model generates outputs related to bus lines and passenger travel times. For each output performance measure, the average and variance are recorded.

*Bus* ***Related Outputs are:***

- Arrival and departure tardiness at different stops, where tardiness = max(actual - scheduled,0)
- Arrival and departure earliness at different stops, where earliness = max(scheduled - actual,0)
- Arrival and departure lateness at different stops, where lateness = actual - scheduled
- Dwell time at different stops, where dwell time is defined to be the difference between the actual arrival time from the actual departure time
- Boarding and disembarking times at different stops
- Holding time at different stops, where holding time = dwell time - boarding/disembarking time
- Waiting time at different stops, where waiting time = holding time - arrival earliness

***Passenger Related Outputs are:***

- Total trip time per passenger for each bus line, which is defined to be the difference between the actual arrival time of the bus to the last stop on the trip for the passenger from the arrival time of the passenger to the originating stop
- Total waiting time among all passengers at a stop, where passenger waiting time is defined to be the difference between the time a passenger arrives to the stop from the time the bus actually departs the stop
- Total delay among all passengers at a stop, where passenger delay is defined to be the difference between the time a bus is scheduled to depart from the time the bus actually departs the stop

## 6. CONCLUSIONS

**A** simulation model which has the capability to replicate an actual bus transit network has been developed. The model will allow us to evaluate the impact of control strategies using ITS versus those without ITS on a wide area network transit system. It is expected that the revised control strategies in the presence of ITS, would greatly improve the performance of the system. The effects would not only be in terms of reduced waiting time for transferring passengers but, also in terms of improved service reliability and schedule adherence. Improvements in the service reliability shall affect the arrival pattern of the passengers to bus stops. With improved schedule adherence, more and more people would time their arrival at a stop with the arrival of the bus. The above phenomena may indirectly lead to drastic reduction in the average waiting time of the passengers. **A** whole set of experiments is being designed, to analyze the impact of ITS under different network scenarios.

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# 8. APPENDIX A

## MATHEMATICAL REPRESENTATION
## OF
## HOLDING STRATEGIES

The following discussion mathematically summarizes the departure time under different holding strategies.

*Control Strategy I (early departure possible)*

$D_i = A_i$

*Control Strategy I (early departure not possible)*

$D_i = \text{Max}\ (A_i, SD_i)$

*Control Strategy 2 (early departure possible)*

$D_i = \text{Max}\ (\mathbf{A_1,..,\&})$

*Control Strategy 2 (early departure not possible)*

$D_i = \text{Max}\ (\mathbf{A_1,...\&,}\ SD,)$

*Control Strategy* ***3*** *(early departure possible)*

$D_i = \text{Min}\ (\text{Max}\ (A_1,..., A_n), (SD, + \text{Holding Time}))$

*Control Strategy* **3** *(early departure not possible)*

$D_i = \text{Min}\ (\text{Max}(A_1,..., \mathbf{A_{,,,}}, SD_i), (SD_i + \text{Holding Time}))$

*Control Strategy* ***4*** *(early departure possible)*

$D_i = \text{Max}\ (t:\ \mathbf{t} < (SD, + \text{Holding Time}) \text{ for } t = \text{TNOW}, F,, F„\ \mathbf{...}, F,)$

*Control Strategy 4 (early departure not possible)*

$D_i = \text{Max}(SD_i\ \mathbf{,}\text{Max}\ (t:\ t < (SD_i + \text{Holding Time}) \text{ for } t = \text{TNOW}, F,, F„\ \mathbf{...}, F,))$

*Control Strategy* ***5*** *(early departure possible)*

$$D_i = \mathbf{Max}\ (\mathbf{t:}\ t < (SD, + \text{Holding Time}) \text{ and } (\sum_{F_j < t} TP_{ji} > \text{Threshold Value})$$
$$\text{for } t = \text{TNOW}, F,, \mathbf{F_2}, \ldots, F,)$$

***Control Strategy 5 (early departure not possible)***

$$D_i = \text{Max}\,(\,SD,, \text{Max}\,(t\text{: } t < (SD, + \text{Holding Time}) \text{ and } (\sum_{F_j < t} TP_{ji} > \text{Threshold Value})$$

$$\text{for } t = TNOW, F_1, F_2, \ldots, F,))$$

***Control Strategy 6 (early departure possible)***

$$Di = (\,t : \text{Min}\,(P_i\,(t - TNOW) + \sum_{F_j < t} (F_j - t)\, TP_{ji} + \sum_{F_j > t} (F_{n(i)} - F_j)\, TP_{ji}$$

$$\text{for } t = TNOW, F_1, F_2, \ldots, F,))$$

***Control Strategy 6 (early departure not possible)***

$$Di = (\,t : \text{Min}\,(P_i\,(t - \text{Max}(\,SD,\,, TNOW\,)) + \sum_{F_j < t} (F_j - t)\, TP_{ji} + \sum_{F_j > t} (F_{n(i)} - F_j)\, TP_{ji}$$

$$\text{for } t = TNOW, F_1, F_2, \ldots, F,))$$

where:

| | |
|---|---|
| $i$ | Index of bus holding at the stop |
| $j$ | Index of any high headway approaching bus to the stop for $j=1,\ldots,n$ |
| $n(i)$ | Index of the next bus arrival for line i |
| $D_i$ | Departure time for bus i |
| $SD_i$ | Scheduled departure time for bus i |
| $A_j$ | Actual arrival time (including the dwell time) of bus j |
| $F_j$ | Forecast arrival of bus j |
| $TP_{ji}$ | Expected number of transferring passengers from bus j to bus I |
| $P_i$ | Number currently on bus i |
| TNOW | Current time |

# 9. APPENDIX B

## SIMULATION DOCUMENTATION

## NETWORK MODEL

This appendix documents the simulation model for wide-area transit networks. The AweSim software package is used to simulate the transit operations. AweSim is a general purpose simulation language distributed by Pritsker Corporation. AweSim was choosen as it has the facility for incorporating user written inserts. The simulation model developed is generic and independent of any dedicated transit network. The model has a high flexibility and can be used to simulate different kinds of transit networks with varying number of bus lines and different travel patterns. The user has the flexibility to input the appropriate control strategy at each stop. With this approach an identical replica of an actual system can be simulated.

### *Entities in the Simulation Network*

There are two types of entities in the simulation model:

- Entities representing the buses in the system.
- Entities representing the passengers.

Entities representing different bus lines are entered into the network at time intervals equaling the headway for their specific bus line. Buses move on their specified sequence of stops until they reach the last stop in their route, at which instant they are terminated. The actual travel time on a bus segment (i.e., path between two adjacent stops) is generated from a normal distribution. The originating passengers for the different bus lines at different stops are known to be of two categories. The arrival times of aware passengers are generated from a normal distribution with mean being slightly before the scheduled arrival time of the bus. Unaware passengers arrive randomly and enter the network at a stop any time between two subsequent runs of a bus line. The number of originating passengers at a stop are generated from a Poisson distribution. The boarding and debarking times from/to the bus are generated using the gamma distribution. Once a passenger boards a bus, the entity representing the passenger is terminated and the bus attribute representing the number of passengers on board is incremented. Each entity in the simulation model has its unique set of attributes, which are collected in the LTRIB array and ATRIB array. The LTRIB array is used to store the integer values while the ATRIB array is used to store real value attributes.

*Bus **attributes are**.*

| **LTRIB #** | **Description** |
|---|---|
| 1 | Line number of the bus |
| 2 | Index representing the number of stops covered in its sequence of M stops |
| 3 | Last stop number visited by the bus |
| 4 | Number of passengers on board |
| 5 | Run number of the specific line |

| **ATRIB #** | **Description** |
|---|---|
| 1 | Arrival time at the last stop visited |

***Passenger attributes are:***

| **ATRIB #** | **Description** | |
|---|---|---|
| | ***Originating*** | ***Transferring*** |
| 1 | Arrival time at the stop | Max of (Scheduled arrival time of the bus, Actual Arrival time of the |

The simulation logic is conducted by user written event nodes. The arrival of originating passengers at a stop and that of the bus are simulated by user-written events. To capture the actual arrival time of the passenger, the creation of entities at a stop is begun one headway ahead of the scheduled arrival time of the bus for each stop in the network. The following sequence of events describe the logic used to simulate the movement of buses.

| **EVENT #** | **DESCRIPTION** |
|---|---|
| 1 | Used to generate the buses for different bus lines. The event initializes the attribute values of the bus entity and reschedules itself to generate the subsequent run of different bus lines. It sends the generated buses to Event **2,** after a time duration representing the actual travel time to reach their first stop. |
| 2 | Represents the arrival of a bus to a given stop. On arrival to a stop the bus |

| | |
|---|---|
| | sends it arrival forecast to the subsequent stops. It calculates the number of transferring passengers and the time it would take to disembark the passengers. Passengers wanting to transfer to another bus are generated and placed in appropriate queues. The attribute representing the number of passengers on board is decremented. The bus is scheduled for Event 3 after a time duration representing the time to disembark the passengers. |
| 3 | Having disembarked all the passengers, the bus goes into the control logic at the arrived stop. After the bus comes out of the control logic, it is scheduled for Event 4, after a time lag of 0 or max(0, TNOW- Scheduled Departure) depending on whether the bus can leave early or not. |
| 4 | Having come out of the control logic, the bus loads the passengers that wanted to get on to the bus. Since the loading of all the passengers who arrive while the bus is disembarking its passengers and while it is waiting at the control logic, takes place during the same duration no extra wait is enforced for the above set of passengers. However, passengers who arrive at the instant the bus got out of the control logic or those who could not board the bus due to the long passenger boarding queue, force the bus to wait for an extra duration for boarding time. The bus is scheduled for Event 5 after a time duration representing the extra time that unboarded passengers might take to board the bus. |
| 5 | The bus is finally ready to leave. It sends its latest forecasts to the subsequent stops and calculates the departure statistics. A check is made to see if the bus has reached its final stop or not. If yes, it is scheduled for Event ***6*** else it updates its attributes to represent the subsequent stop. Actual travel time for the leg is calculated and the bus is scheduled back to Event 2 after a time lag equaling the actual travel time |
| 6 | The arriving bus is terminated, representing the completion of a run for a bus line in the transit network. |

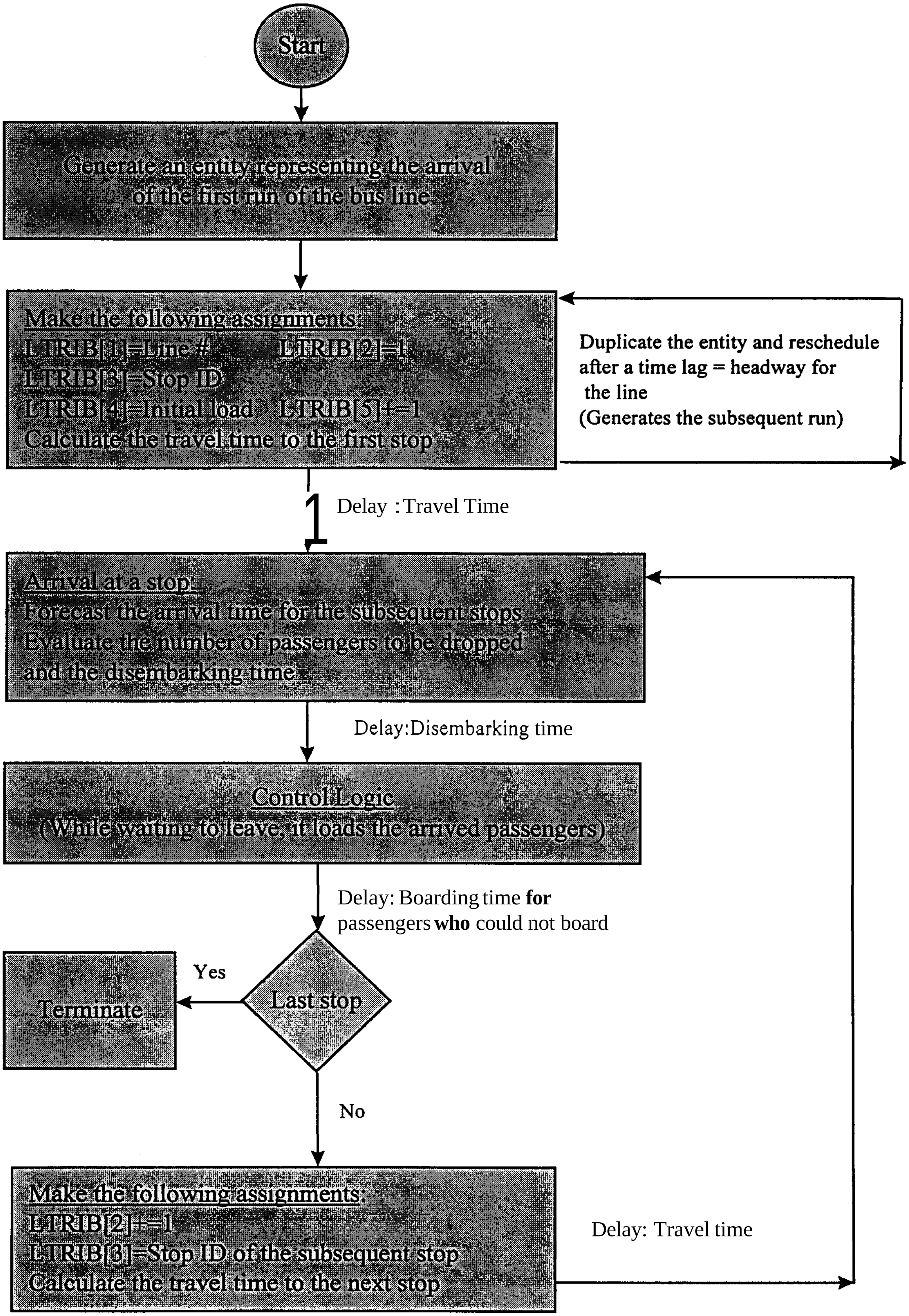
The following Event nodes are used to generate the arrival of originating passengers to a stop.

| EVENT # | Description |
|---|---|
| 7 | Dummy entities representing the originating passengers arrive one headway ahead of the scheduled arrival of buses , at its various stops. It generates the number of passengers that would board the bus at the given stop. Having generated the number of passengers, it splits the arriving passengers into |

| | |
|---|---|
| | aware and unaware category. It then assigns all the originating passengers an arrival time and schedules their arrivals to Event **8** at times representing their actual arrival times. The dummy entity reschedules itself to Event **7** after a time lag equalling the headway of the bus line for which it is generating the originating passengers. |
| **8** | The entities representing the originating passengers arrive to a stop. On their arrival, they go and wait in appropriate queues for their respective buses. |

Flow charts showing the logic for bus movement and the different dispatching rules are shown next in Figures 1 - 5.

Figure 1. Flow Diagram for Movement of Buses Along Its Route



## Fipure 2. Control Lopic: No Hold

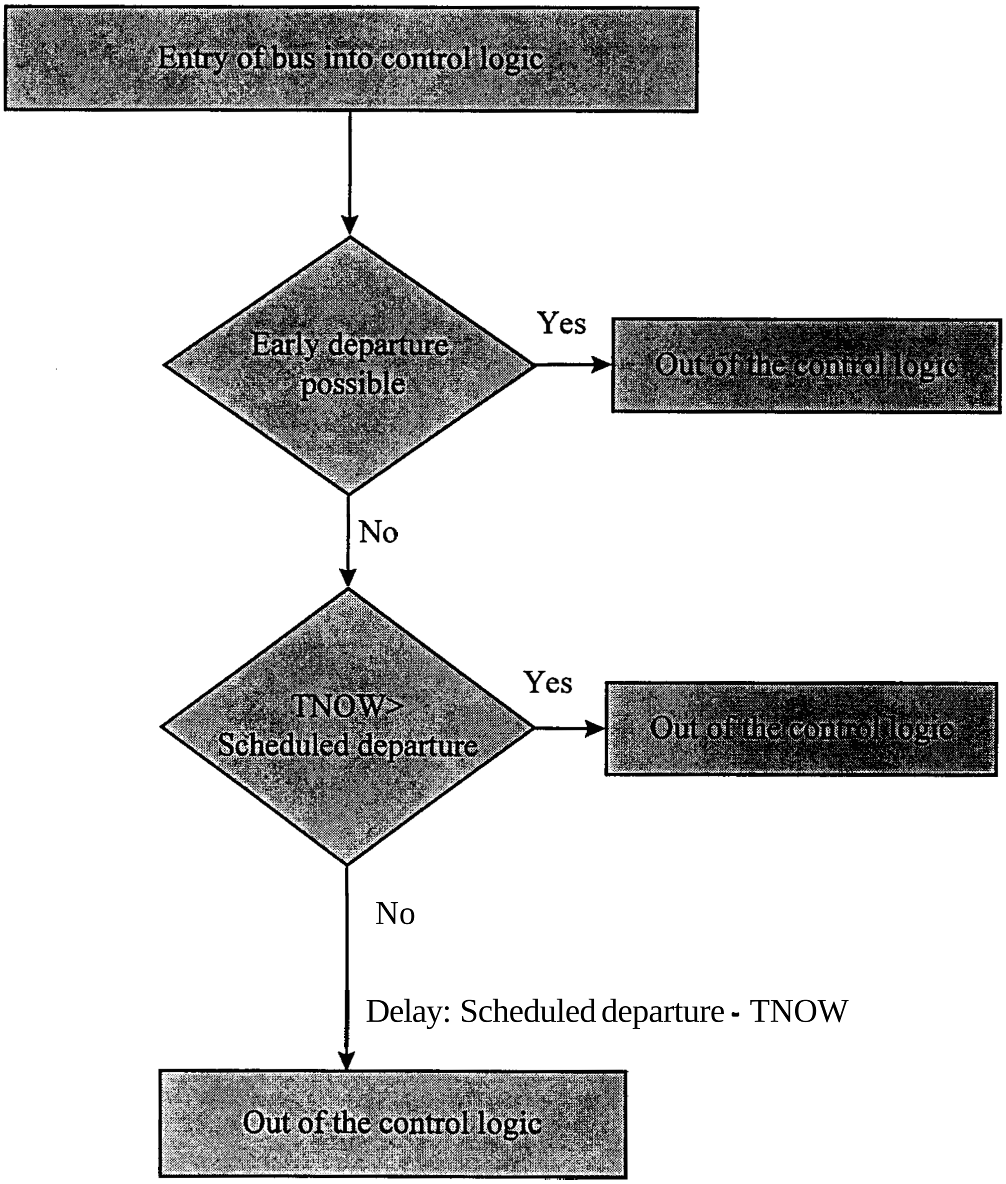


**Figure 3. Control Lopic: All Hold**

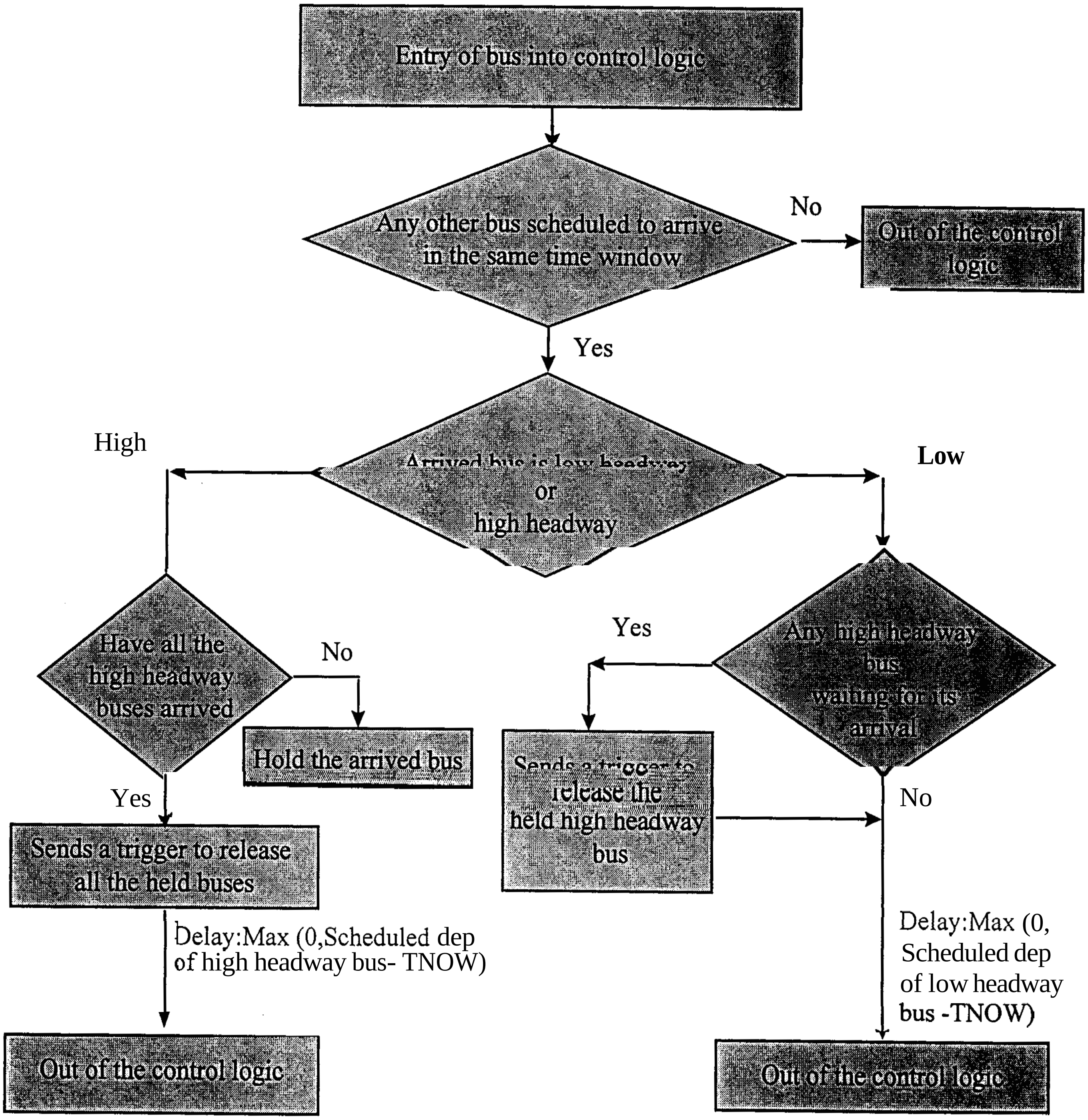


**Figure 4. Control Logic: All Hold With a Maximum Waiting Period**

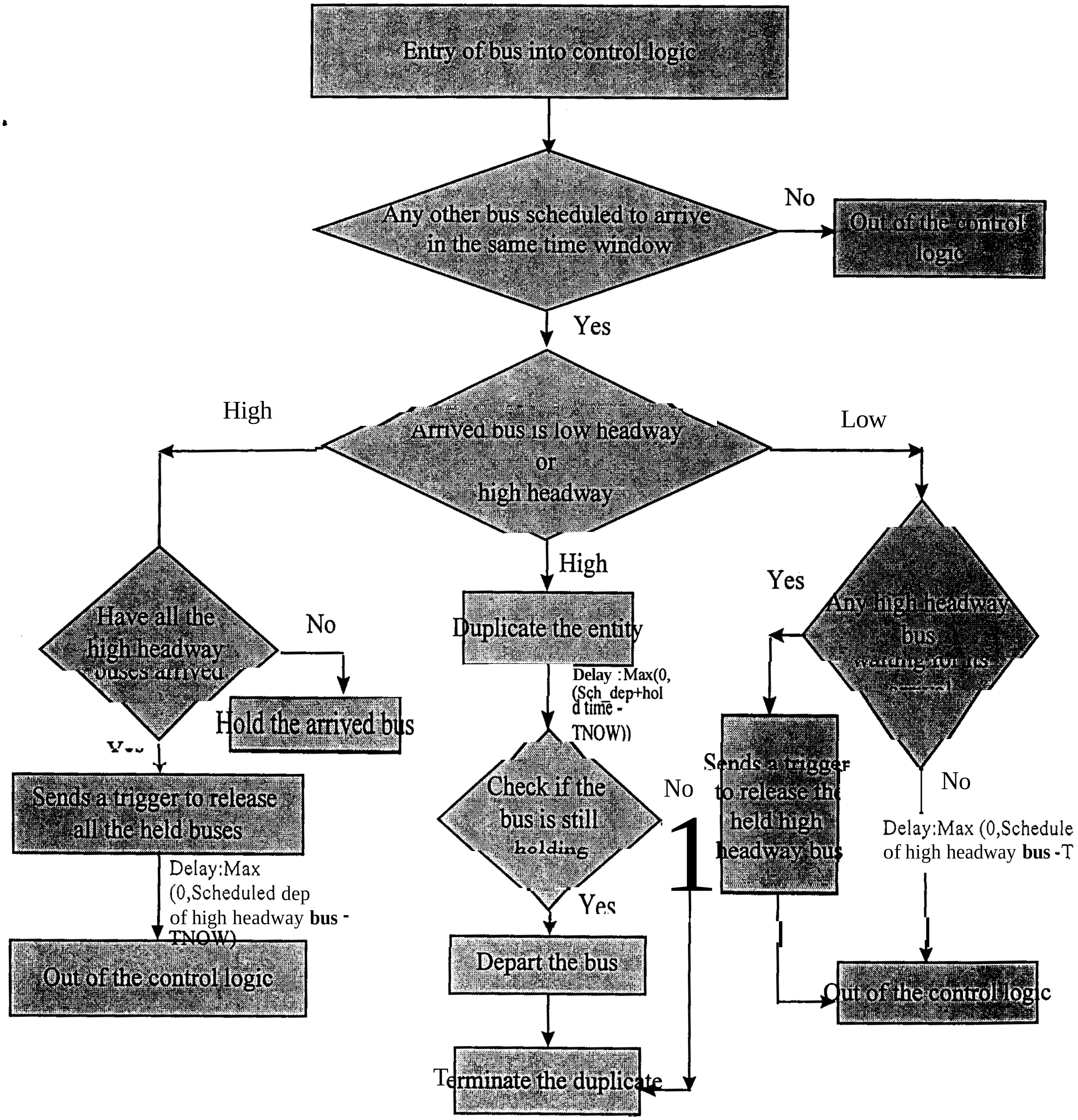


**Figure 5. Control Logic: Forecast and Hold if the Forecasted Arrival is Within the Holding Time**

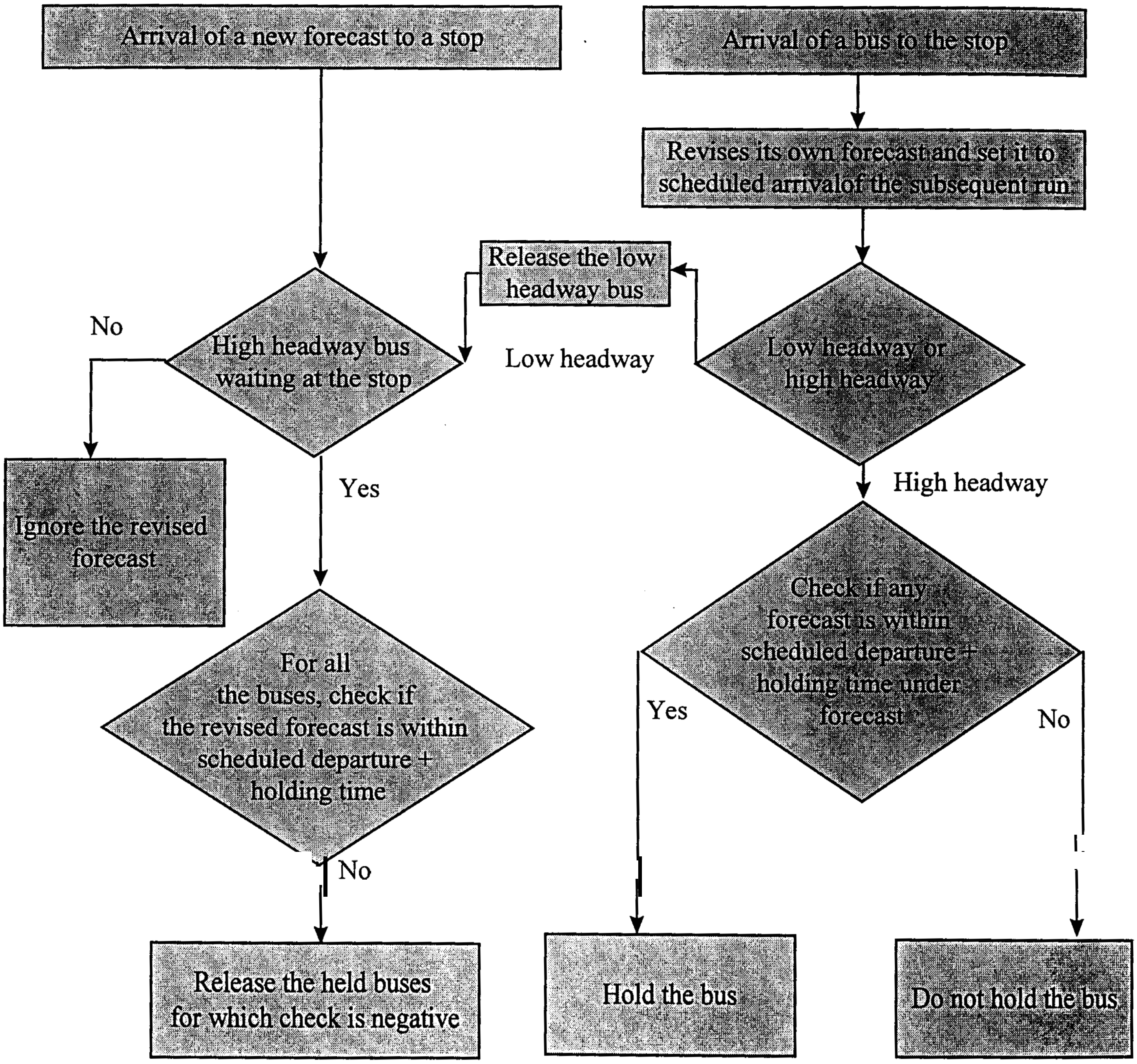


**Figure 6. Control Logic: Forecast and Hold if the Forecasted Arrival Is Within the Holding Time and the Transferring Passengers are Greater Than a Threshold Value**