

**BUS DISPATCHING AT TIMED TRANSFER  
TRANSIT STATIONS  
USING BUS TRACKING TECHNOLOGY**

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## **ABSTRACT**

A timed transfer terminal synchronizes the arrival of incoming vehicles with the departure of outgoing vehicles so as to minimize transfer delays. Most bus timed transfer terminals follow fixed schedules, and do not utilize intelligent transportation systems for vehicle tracking and control. This paper reviews technologies that enable real-time control of timed transfer. We evaluate the benefits of tracking bus locations and executing dynamic schedule control through the simulation of a generic timed transfer terminal under a range of conditions. Based on empirical data collected by the Los Angeles County/Metropolitan Transit Agency, we found delay over segments of long-headway bus lines to be negatively correlated with lateness at the start of the segment, indicating that buses have a tendency to catch up when they fall behind schedule. The simulation analysis showed that the benefit of bus tracking is most significant when one of the buses experiences a major delay, especially when there is a small number of connecting buses.

**Keywords:** Timed Transfers, Holding Times, Delay Distributions, Intelligent Transportation Systems

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## 1. INTRODUCTION

A timed transfer exists when multiple bus routes are scheduled to arrive on or about the same time at a transit terminal, with the goal of enabling short waiting times when transferring between buses. Timed transfers have become increasingly common in bus systems, because they provide greater connectivity between origins and destinations, especially for bus lines with large headways. Clever (1997) outlines the increased integration of timed transfer terminals with other transit services such as rail in several European countries including Germany and Austria.

Most major airlines have established “hub-and-spoke” type networks in which flights are funneled through a limited number of airports. Flights are scheduled in and out of these airports in flight "banks", a period on the order of one hour in which up to 100 flights may arrive and depart. Like bus systems, the objective is to provide greater connectivity between origins and destinations, while minimizing waits. When an incoming flight is delayed, airlines have the option of holding other flights to allow passengers to make connections, or alternatively departing on schedule. The decision on whether to hold a flight or not depends on a variety of factors, including: (1) magnitude of delay, (2) number of connecting passengers, and (3) frequency of service on the connecting flight. Furthermore, real-time information regarding these factors enables controllers and pilots to make decisions regarding whether to increase or reduce the travel speed in order to provide greater connectivity.

These same considerations are also important to bus systems. However, bus systems have historically lacked real-time information regarding vehicle location and number of passengers intending to transfer to make similar dispatching decisions. 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 (Khattak

et al., 1993; Hansen et al, 1994; Hickman et al, 1996). GPSs are particularly useful for vehicle tracking and mobile data terminals may be used for passenger counting.

There exists some literature on scheduling timed transfers in the presence of random delays. Based on the probability distribution for schedule "lateness", arrival and departure times are optimized, accounting for the likelihood of making a transfer connection and the expected waiting time for the transfer connection. Hall (1985), for instance, examines transfers to and from a rail line, and develops formulas for optimal "safety margins" (i.e., the expected time between arrival of an inbound bus and an outbound train). U.S. UMTA (1983) and Vuchic et al (1981) provide fairly comprehensive manuals for design of timed transfer systems. Abkowitz et al (1987) simulate a variety of dispatching strategies at a timed transfer hub. Their simulation results on two bus lines show that a no holding strategy is best when the bus lines have unequal headways and a double holding strategy is best when the bus lines have equal headways. Lee and Schonfeld (1992) simultaneously optimize headways and safety margins at a timed transfer terminal. Shih et al. (1997) develop a trip assignment model for timed transit terminals. Application of their model to an example network shows that demand tends to be assigned to higher frequency paths in uncoordinated cases.

In this paper, we augment the prior work on timed transfer terminals by evaluating the performance of dispatching rules with ITS versus 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. Performance measures that are studied include total passenger delay and number of passengers missing their connections.

An input to the simulation model is the probability distribution of delay at each stop. Prior studies on lateness or delay distributions focused on bus lines with frequent service (i.e.,

small headways). For example, several authors (e.g., Turnquist, 1978; Andersson and Scalia-Tomba, 1981) argue that for this environment an initial delay in service causes deteriorating service farther down the line due to the increasing accumulation of boarding passengers as the headway becomes larger than scheduled. Our interest is on bus lines with large headways since there is little benefit to coordinating bus transfers if the headways are small. For bus lines with large headways the opposite effect may result. That is, service may not deteriorate as the bus moves farther down the line because there may be sufficient slack in the schedule to enable the bus to get back on schedule.

The remainder of this paper is divided into four sections. First, we review technologies that enable real-time control of timed transfer. Second, we develop a model for bus delay over segments and lateness arriving at check points based on empirical data collected from the LA County/Metropolitan Transit Agency (LAC/MTA). Third, a simulation model is created and used to compare different strategies for controlling bus dispatch times. The final section provides conclusions.

## **2. TECHNOLOGY FOR TIMED TRANSFER**

In the absence of communication and tracking technology, timed transfer systems must rely on set schedules, combined with driver observations, for bus coordination. Buses can be held beyond their normal departure time if drivers observe that connecting buses are late. However, they can have no idea of how late the buses will be, or whether they will arrive at all. Some bus systems utilize voice-radio systems to coordinate transfers, allowing drivers to inform dispatchers of when they are running late. The information can then be relayed to buses that

have already arrived at the timed transfer terminal, so that they can determine whether it is worthwhile to wait.

Intelligent transportation systems go one step further, allowing for regular monitoring of bus status, and automated execution of control rules, without the necessity for driver intervention. The basic technological components of an advanced timed transfer system are:

1. Automatic Vehicle Location (AVL) System
2. Mobile Data Terminal for Driver Interface
3. Wireless Communication System
4. Transit Operations Software and Hardware
5. Passenger Interface, Passenger Counter and/or Electronic Fare Payment (optional)

All of these products are readily available as commercial products, with the exception that base station systems typically are not programmed to provide timed transfer functionality. However, this amounts to a simple modification of existing software. A timed transfer system does not require vehicle component monitoring, traffic signal priority, or traveler information.

The method of operation entails tracking the location of vehicles, and then executing control actions if a vehicle is determined to be behind schedule. The control action can either be to hold or to release a connecting bus at the transfer terminal. The action is communicated from the base station to the connecting bus through either voice communication (e.g., conventional radio) or through transmitting a digital message to the driver's mobile data terminal. The control action can be conditioned to information on the number of passengers on board the late bus or the number of passengers transferring from the late bus. Automated passenger counters and electronic fare boxes can be used to track the number of passengers on board. However, transferring passengers can only be counted accurately if passengers register their destination,

either directly (e.g., a mobile data terminal accessible to passengers) or indirectly (the driver asks passengers where they are going, and registers this information for them).

The Federal Transit Administration in the United States regularly tracks deployment of advanced technologies in buses. Casey et al (1996,1997) and Casey (1999) provide case studies, and tables showing the technologies that have been deployed in individual agencies. Morlok et al (1994) also describes several installations as part of developing a cost-benefit evaluation methodology.

## **2.1 AVL Systems**

Automatic Vehicle Location (AVL) is the core system component. The system works by measuring the real time location of each vehicle and transmitting the information to the base station. At the control center, transmitted information is processed and the location of the bus is graphically displayed on an electronic map. Three different technologies are currently used: (1) Signpost and odometer (SO), (2) Global Positioning System (GPS), and (3) Radio Navigation, as described in the following. For a more in-depth review of AVL technologies, see Okunieff (1997).

**Signpost and Odometer (SO)** SO was at one time the dominant vehicle location technology. The system uses radio beacons mounted on top of utility poles. Each beacon has a unique I.D. Beacons send a low powered signal, which is detected by vehicles fitted with receivers. When it is time to report, vehicles send the I.D of the last beacon crossed and the distance traveled. An alternative to the above approach is to associate a unique I.D with each bus. When a bus passes a signpost, its position is relayed back to the control center. Implementing the alternative

approach has the advantage of eliminating the need for wireless transfer of data from the vehicle; however, it suffers from the drawbacks that stray vehicles fail to send information to the control center. SO suffers from the following drawbacks:

- Signposts can only be placed at a small number of locations. If vehicles stray into locations that do not have signposts, their positions cannot be detected.
- It is costly to install, as it involves mounting radio beacons in the field.
- Requires a high degree of maintenance.

**Global Positioning System (GPS)** GPS is the most commonly used technology in new installations. According to Okunieff, “Only agencies who procured their system in the 1980s or earlier 1990s or who are upgrading their existing signpost system are choosing signpost technology.” GPS utilizes the signal transmitted from a constellation of 24 satellites along with receivers mounted on the roof of each bus. The bus reads the signal and transmits its latitude and longitude to the base station. The advantages of GPS are:

- It works anywhere the satellite signals reach
- It requires no field infrastructure. Since the satellites are already in orbit, the application of GPS technology only involves installing the receivers on buses.

The disadvantages of GPS are:

- The satellite signals do not reach underground and can be obstructed by tall buildings. Hence, GPS has to be supplemented with signposts or with compass/odometer to determine the location of vehicles in some locations.

- To obtain high accuracy, “differential GPS” (DGPS) must be used. Under DGPS, a receiver is placed at a known position. The difference between the exact location and the GPS measured location is used to improve the accuracy of the position determination of vehicles.
- A wireless system is required to communicate between vehicles and the base station.

Functionally, GPS systems can operate something like signpost/odometer, in that they usually only communicate their status when passing schedule check points (i.e., key bus stops). The arrival or departure time at the stop is determined by comparing the bus’s latitude/longitude to the recorded latitude/longitude of the bus stop. For greater accuracy, a door sensor can be installed, to determine exactly when the door opens and closes. The deviation between scheduled time and actual time is then communicated back to the base-station, which can execute appropriate control actions. GPS systems can also poll vehicles at set time intervals, or under exception conditions. GPS systems typically do not provide continuous, or near-continuous, tracking, due to communication requirements.

**Radio Navigation** Ground based radio navigation (Loran-C) uses low frequency waves to provide coverage. It determines location, based on the reception of transmissions and the associated timing. Ground based radio navigation is susceptible to interference, and proximity to overhead power lines causes significant error. However, Teletrac, a company in Los Angeles, has been successful in utilizing radio navigation for location of vehicles, which it offers as a commercial service.

A variety of communication media are available for transmitting messages, including commercial radio, cellular and satellite. Economic factors typically drive the choice. No matter

which medium is selected, two methodologies are available for data transmission from the bus to the control center:

- **Polling:** each bus is polled in sequence. The accuracy of information transferred depends on how fast the buses are polled. Since different channels can be used for this purpose, the polling frequency of each bus could be quite high.
- **Exception Reporting:** buses report to the base station only when it runs off the schedule beyond a specified tolerance. Exception reporting requires that buses not only to know their present location but also their scheduled position. This increases the hardware and software requirements, making it costlier to install.

## **2.2 Automatic Passenger Counters**

Automatic passenger counters (APC) are an automated means of collecting data on passengers boarding and alighting by time and location. For an in-depth review of technologies, see Boyle (1998). The data may be used in real time or later for different applications. Some of the uses of data collected are:

- Input to dispatcher decision for immediate corrective action
- Input to real time passenger information system
- Future scheduling
- Positioning new shelters
- Fleet Planning

Automatic Passenger Counters have the following advantages: (1) Decreased data collection, (2) Decreased time and effort for data processing, (3) Increased operating efficiency,

and (4) Enhanced data for passenger information systems. Infrared beams and treadle mats are the two most common technologies:

- *Infrared Beams*: Two infrared beams are placed across a passenger's path. As passengers board and alight the bus, they interrupt the beam in a particular sequence, thus activating the APC device. This is the most common technology.
- *Treadle Mats*: Two treadle mats are placed on the steps of doorway. The pressure of passengers stepping on them activates the APC.

Over the last couple of years transit agencies have also introduced the concept of electronic fare payment to eliminate cash/coin handling, automate accounting, eliminate moving parts in fare boxes and to make fare schedules more sophisticated. Electronic fare boxes also provide a capability for counting boardings

Electronic fare payment systems employ electronic communication, data processing and data storage techniques. Some of the most popular ones are:

- *Magnetic Strip card*: Magnetic strips are imprinted on cards. The magnetic strip stores the cash content of the card. On use, the card gets charged, reducing its cash balance.
- *Contact Type Integrated Circuit Smart Cards*: Each card contains a microcomputer, along with an EEPROM (electronically erasable programmable read-only memory) and ROM (read-only memory). While the ROM is used to store the cash content on the card, EEPROM is used for storing the operating system, for performing the transaction and identification. Since, the card allows for user identification, it is safer against theft.

- *Proximity Cards*: The proximity cards do not require the card and reader to be in contact, thus making the payment process more comfortable for users. The system uses a radio frequency (RF) magnetic field generated from inductive coil on the read/write unit of the bus to power the card's circuitry.

### 3. PROBABILITY DISTRIBUTION MODEL FOR DELAY

If buses closely adhere to their schedules, there is little reason to utilize the technologies described in Section 2 for timed transfer. Departure times can be pre-set, with minimal or no active real-time control. Unfortunately, most transit systems experience a fair degree of unpredictability, due to randomness in roadway travel times and randomness in bus dwell times. This section models this randomness, as a means to determine the effectiveness of technology in timed transfer.

We define *lateness* as the deviation from the scheduled arrival time at a check point or stop and *delay* as the deviation from the scheduled travel time over a segment. The relationship between lateness and delay can be expressed as follows:

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

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

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 the 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 than likely to be behind schedule than ahead of it. Some authors select the probability distribution based on empirical studies (e.g., Turnquist, 1978; Talley and Becker, 1987; Guenther 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).

**INSERT TABLE 1 HERE**

These past studies are not directly applicable to our situation since (1) they are intended for frequent service bus lines (i.e., small headways) or (2) they do not consider the relationship between delay and lateness for adjacent bus stops. The correlation between delay and lateness is especially important in modeling bus lines. Turnquist (1978) observed that an initial delay in service on a short headway line causes deteriorating service downstream due to increased boardings. Hence, the random variables  $L_{k-1}$  and  $D_k$  are positively correlated on short headway lines.

For bus lines with large headways, service would not necessarily deteriorate downstream, as passengers are likely to plan their arrivals at bus stops according to the bus schedule. Past studies indicate that 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). Since our focus is on high headway bus lines, the majority of the boardings can be considered passengers aware of the bus scheduled arrival time. Hence, a high headway bus will not carry additional boardings if behind schedule. Additional boardings may occur for short headway buses because of the random arrival times of unaware passengers causing the well-known vehicle bunching phenomenon.

In fact for high headway bus lines, it may be that buses have a tendency to catch up when they fall behind because most bus schedules contain built in slack. This is reinforced by operator policies that penalize drivers when they operate as little as 30 seconds ahead of schedule, or when they fall significantly behind schedule. Therefore, we hypothesize that  $L_{k-1}$  and  $D_k$  are negatively correlated on long headway lines. That is, the later the arrival time of a bus to a stop, the more likely that the delay on the next segment will be smaller. We test this hypothesis and develop a new delay probability distribution function for infrequent service bus lines based on data generated by LAC/MTA.

### Description of LACMTA

The LAC/MTA operates almost 200 bus routes and has more than 2500 buses in the fleet. Bus service is provided 24 hours a day with limited service during late night hours. Currently, MTA coordinates timed transfer stations at three locations with the biggest being at 7<sup>th</sup> and Broadway operating at night. Once a year, a person is assigned by the MTA to collect data on each scheduled trip of each bus line. The data consist of actual arrival times, the number of passengers boarding and alighting, and fare types used at all stops. These data are entered into a hand held computer with an internal clock, so that arrival times are accurately recorded to a tenth of a minute.

The data consist of three routes in Los Angeles (LA) County, all converging in the downtown area of LA near the timed transfer center at 7<sup>th</sup> Street and Broadway Street. The three routes were chosen for their route locations and the fact that they have no stops in common which is necessary so that the only interaction between the routes will be at the timed transfer station. Data were collected from both directions of the route. Hence, there was a total of six routes analyzed. In a report, Mourikas (1997) presents in detail the complete statistical analysis of the results. We briefly summarize the results of this analysis for two of the bus routes, #26 eastbound and #30 westbound. We note that the findings for the other routes exhibit similar characteristics as these two routes. Bus line #26 has 17 major stops and bus line #30 has 11 major stops. All the stops contain data from at least 30 trips. Both lines operate with a headway of 60 minutes at night. Each route had around 1250 arrival time observations collected, providing an ample dataset for statistical analysis. The data were collected during the week from Monday to Friday. Weekends were excluded since buses run on different schedules than on weekdays. The data was collected over a 24-hour period on ten days in April 1995 for route #26 and on nine days in November 1995 for Route #30.

To demonstrate the relationship between the delay and lateness for adjacent stops, Table 2 shows the correlation results of the data collected from bus lines 26 and 30. We also list the t-statistic for each correlation coefficient for the hypothesis that it is equal to zero. Based on the t-statistic, all the correlation coefficients listed in the table are significant at a 99.5% confidence level since  $t_{.995} = 2.57$ . As expected, the lateness values at adjacent stops ( $L_{k-1}$  and  $L_k$ ) are positively correlated, meaning that if a bus is late at a stop it is also likely to be late at the next stop. This result implies that buses do not recover immediately from disturbances that place them behind (or ahead) of schedule. However, buses can at least partially recover from their lateness, as reflected in the negative correlation between  $D_k$  and  $D_{k-1}$  and between  $D_k$  and  $L_{k-1}$ . Hence, high headway buses have a tendency to catch up when they fall behind because most bus schedules contain built in slack.

**INSERT TABLE 2 HERE**

A Conditional Probability Model for Delay

To further demonstrate the effect of lateness on delay, Figure 1 plots the delay on segment  $k+1$  versus the lateness at stop  $k$  for bus line #30. The mean delays, shown on the solid line, are not centered on the actual values because each tick may represent more than one observation. The plot shows that buses travel slower when ahead of schedule and faster when behind schedule. The plot suggests the following linear relationship for the expected delay,  $E(D_k | L_{k-1})$ , on segment  $k$ .

$$E(D_k | L_{k-1}) = \alpha + \beta L_{k-1} \quad (3)$$

The constant value,  $\alpha$ , can be interpreted as the expected delay on segment  $k$  when the bus is on-

time at the previous stop and the slope,  $\beta$ , is the correction factor when the bus is not on-time.

### **INSERT FIGURE 1 HERE**

Figure 1 also shows the results of the regression analysis and the dashed line shows the regression line. Although the  $R^2$  value is low in our model, the statistical model shows that our results are statistically significant. In fact, the significance level is extremely high (a level of  $1.1644E-17$  as shown in Figure 1). A low value of  $R^2$  implies that there is a high level of natural variability in the arrival lateness that cannot be explained by the model. This natural variability is simply part of the random bus arrival time process. However, the portion that can be explained is statistically significant as shown by the results in Figure 1. For bus line #30,  $\alpha = .23$  (min) and  $\beta = -.29$ . We note that we found that Eq. (3) also holds for bus line #26 with  $\alpha = .06$  (min) and  $\beta = -.28$ .

The above analysis assumed that the travel times between the stops for the Los Angeles County data are identical. Since the studied routes centered around Downtown Los Angeles where the buses make frequent stops, the equal spacing assumption was valid for these routes.

To derive the conditional probability density for delay given the lateness,  $f(D_k | L_{k-1})$ , the frequency distribution of the observed delay was evaluated over given ranges of lateness. We divided the lateness into five intervals:  $(-\infty, -2]$ ,  $(-2, 0]$ ,  $(0, 2]$ ,  $(2,4]$ , and  $(4, \infty ]$ . Figure 2 shows the resulting frequency distribution of delay over each lateness interval superimposed on a normal probability density function for bus line #26. The figure also lists the mean and standard deviation of delay for each lateness interval. Although the expected delay clearly depends on the lateness, there does not appear to be any relationship between the standard deviation of delay and lateness. The figure also shows the result of the Kolmogorov-Smirnov Test for each lateness interval. At a 95% confidence level, the hypothesis that the conditional

probability density of delay given the lateness,  $f(D_k | L_{k-1})$ , is a normal distribution cannot be rejected. We note that this analysis was performed for several other distributions such as lognormal and gamma and the normal distribution gave the best fit for the given data set.

**INSERT FIGURE 2 HERE**

Some of the simulations that appear in Section 4 are based on major schedule disturbances that place buses as much as 30 minutes behind schedule. In such instances, the model of Eq. (3) is unlikely to apply due to insufficient slack in the schedule. Therefore, for our simulations, the catch-up capability of a bus was truncated according to our estimate for the slack imbedded in the schedule. This is represented in the following relationship:

$$D_k = \max ( \gamma (S_k - S_{k-1}), \text{Normal} (E(D_k | L_{k-1}), \sigma ) ) \quad (4)$$

where:

$\gamma$  = the slack as a proportion of the schedule segment travel time

The expected delay,  $E(D_k | L_{k-1})$ , is derived from Eq. (3) and  $\sigma$  is the standard error. From Figure 1, the standard error of delay for bus line #30 is 1.22 minutes. Analysis of data from LAC/MTA suggest that  $\gamma$  is on the order of .25, meaning that actual travel time over any segment can be no less than 75% of the scheduled travel time, even when far behind schedule.  $\gamma$  is estimated by calculating the ratio of the maximum earliness over the scheduled travel time.

Forecasts Utilizing Tracking

In the presence of a bus tracking system, arrival times can be forecasted for a timed transfer terminal using the conditional distribution model. We assume that the forecast is updated each time the bus passes a schedule check-point. The forecast arrival time is the sum of

the scheduled arrival time at the transfer terminal and the forecast lateness time at the terminal. The forecast lateness is the sum of the forecasted delays over the segments between the current check-point and the transfer terminal and the current lateness. We adopt the non-truncated model in this section, which should be accurate in the absence of unusually large schedule disturbances:  $E(D_k | L_{k-1}) = \beta L_{k-1} + \alpha$ . We assume that the conditioned distribution for  $D_k$  is normal, with variance independent of  $L_{k-1}$ . Finally, for the sake of simplicity, we assume that the delay distribution is identical for all line segments.

Let  $L_0$  be the lateness at the current stop. Then, the expected lateness at the next stop can be calculated as:

$$E(L_1) = (1+\beta)L_0 + \alpha \quad (5)$$

The expected lateness at all subsequent stops (including the transfer terminal) is iteratively determined:

$$E(L_k) = (1+\beta) E(L_{k-1}) + \alpha, \quad k > 1 \quad (6)$$

The variance of the lateness can similarly be derived from Eq. (6) by solving for the expectation of  $L_k^2$  conditioned to  $L_{k-1}$ , and subtracting  $E^2(L_k)$ , yielding the following result:

$$V(L_k) = V(L_{k-1}) (1+\beta)^2 + V(D) \quad (7)$$

where  $V(D)$  is the variance of the delay on an individual segment.

As  $k$  becomes large,  $E(L_k)$  approaches a limiting value, which is found by solving for  $E(L_k) = E(L_{k-1})$ , resulting in:

$$E(L) = -(\alpha/\beta) , \quad \text{large } k \quad (8)$$

$V(L_k)$  also approaches a limiting value:

$$V(L) = -V(D)/(2\beta + \beta^2), \quad -2 < \beta < 0, \text{ large } k \quad (9)$$

For the lines studied at LAC/MTA, the limiting value of  $E(L)$  is on the order of .5 minutes, and the limiting value of  $V(L)$  is on the order of  $3 \text{ min}^2$ , indicating a good level of schedule adherence. For values of  $\beta$  smaller than -2 or greater than 0, lateness is naturally unstable, with the variance growing without bound as  $k$  becomes large. The variance is minimized when  $\beta = -1$ , for which  $V(L) = V(D)$ .

#### 4. SIMULATION MODEL

A simulation model of a timed transfer terminal is developed to evaluate the performance of dispatching rules with ITS versus those without ITS. The model is developed using a general-purpose simulation language, SLAMSYSTEM (Pritsker, 1986). The advantage of using a process-oriented language to model bus operations is that a small generic network, which has the flexibility to test many different dispatching strategies, can be used to represent detailed bus movement.

We developed a simulation model of a generic timed transfer station. It is assumed that the simulated bus lines only connect at the transfer station. Hence, the bus route network is a collection of straight lines with an intersection at the transfer station. The purpose of this analysis is to evaluate the performance of a timed transfer terminal under a range of conditions, to see where technologies are most effective. It is intended as a design tool, to guide future implementations, and to determine whether technology should be used. It was not developed to evaluate a current terminal, but to see how they should be created in the future.

The scheduled arrival times at each major stop and at the timed transfer terminal 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 reaches the timed transfer terminal. The actual travel time on each segment,  $A_k - A_{k-1}$ , is the scheduled travel time plus the delay:  $S_k - S_{k-1} + D_k$ . We use Eq. (4) to sample the delay on the segment,  $D_k$ . Consistent with the simulation model of Seneviratne (1990) we assume that the distribution on the number of boarding passengers at each stop is Poisson distributed. Since we are only concerned with predicting the behavior of the system at the terminal, the model simulates only the passengers that stay on the bus until they reach the terminal (i.e., passengers that exit prior to the terminal are not simulated). Since we are only concerned with long headway lines, the model does not attempt to correlate travel time to the number of passengers boarding and exiting.

We model the detailed movement of a bus along its line instead of sampling a single arrival time at the terminal, which was the approach used by Abkowitz (1987), to allow for bus tracking capabilities and the subsequent mechanism to forecast its arrival time to the timed transfer terminal. The forecast arrival times are not 100% accurate. The forecast arrival time to

the terminal at any instant of time is the scheduled arrival time plus the expected arrival lateness to the terminal, which is based on its current location, and is iteratively calculated using Eq. (6). The actual arrival times are random variables drawn from the conditional delay and lateness distributions given in Section 3.

Two levels of ITS are considered: (1) system with centralized tracking and (2) system with information on connecting passengers, as well as centralized tracking. The tested strategies are:

- 1) Hold until all scheduled buses have arrived
- 2) Do not hold and dispatch bus at the maximum of its scheduled departure time and actual arrival time
- 3) Hold the bus for a maximum period of 1.5 minutes if all scheduled buses have not arrived
- 4) Forecast bus arrivals and hold if another bus is expected to arrive within 1.5 minutes
- 5) Forecast bus arrivals and hold if another bus is expected to arrive within 1.5 minutes and has at least one passenger who plans to transfer to the holding bus
- 6-8) Same as Strategies 3-5, except hold time is changed to 3 minutes.

Strategies 4 and 7 require bus tracking while Strategies 5 and 8 require bus tracking as well as passenger counting capabilities.

The parameters used for the simulation model are as follows. Each bus line is scheduled to depart from the terminal at the same time. We assume 24 major stops which are uniformly spaced with a duration of 2.5 minutes giving a scheduled trip time to the terminal of 60 minutes. The expected number of passengers boarding at each stop is the same with a mean of .42 which

gives an expectation of 10 passengers on the bus when arriving at the terminal. We had no data on the probability distribution on the number of passengers transferring. We assumed that a passenger was equally likely to transfer to any given bus line at the timed transfer station. Based on the data analysis in Section 3, we initially set  $\alpha = .20$  min.,  $\beta = -.30$ , and  $\gamma = .25$  for each bus segment. We later discuss the sensitivity of the results to different values of all the above mentioned parameters.

A summary of the simulation results is provided in Figure 3. We show the results for three different cases representing 2, 5 or 10 bus lines connecting at the terminal (N=2, 5, and 10). Included in the figure are the average departure lateness and the fraction of passengers missing their connection of 500 simulation runs for each scenario.

**INSERT FIGURE 3 HERE**

In addition to plotting the averages, a pair-wise statistical analysis using the Newman-Keuls Test (Anderson and McLean, 1974) was conducted. The results shown below are for a 90% confidence level. An underline between two strategies indicates that the difference between the means are statistically insignificant.

Departure Lateness

N = 2:    2 4 5 3 7 8 6 1

N = 5:    2 4 5 3 7 8 6 1

N= 10:    2 4 5 3 7 8 6 1

Fraction Missing

N = 2:    1 6 7 8 3 4 5 2

N = 5:    1 6 7 8 3 4 5 2

N = 10:    1 6 7 8 3 4 5 2

As expected, the all hold strategy (#1) has the highest average departure lateness but has no passengers missing their connections. Alternatively, the do not hold strategy (#2) has the most passengers missing their connection and the smallest departure lateness. Comparing strategy 3 with 4 and strategy 6 with 7 shows the impact of bus tracking, as the former lacks a forecasting ability. On average, bus tracking reduces the departure lateness by about 20 seconds without a subsequent increase in the number of passengers missing their connections. Comparing strategy 4 with 5 and strategy 7 with 8 shows the impact of passenger counting. In our simulations there is a high likelihood that a passenger will be transferring to a holding bus. Therefore, passenger counting provides little added value and the two strategies are almost identical.

Figure 3 also plots the ratio of the total passenger delay for the given scenario over a lower bound which gives minimum average waiting time with complete information (i.e., all actual arrival times are known, Hall et. al., 1997). As Figure 3 shows, the all hold strategy provides the best ratio to the lower bound. However, this strategy is not a realistic one to implement since it yields unusually high bus departure lateness at the terminal that will have detrimental effects on subsequent stops. Due to the high penalty of missing a bus (i.e., large bus headway), Figure 3 shows that it is preferable to use a holding time of 3 minutes as opposed to 1.5 minutes. In this case, holding for a fixed amount of time (Strategy 6) and the forecasting strategies (Strategies 7 and 8) are the best performing strategies based on the total passenger delay criterion.

Figure 4 shows the sensitivity of the results for the forecasting strategy as a function of the maximum holding time. As the maximum holding time increases, the rate of increase in the average departure lateness is the greatest when the number of transferring buses is large (e.g.,

N=10). For the given data set, a maximum holding time greater than 3 minutes gives an average departure lateness of more than 4 minutes, and the lateness starts to significantly increase as the holding time increases, especially when N=10. In terms of the fraction of passengers missing their connection, the rate of decrease is the greatest when N is small. The graph shows that a holding time over 8 minutes is the closest to the lower bound although it gives a high average departure lateness at this level. This holding time is much larger than the expected arrival lateness due to a high penalty associated with missing a bus with a large headway in the total passenger waiting time function. We do not recommend using a holding time this large because it would be too disruptive to the downstream schedule.

#### **INSERT FIGURE 4 HERE**

We next study the impact of ITS when one of the connecting buses experiences a breakdown or major delay. For these scenarios, we randomly selected one of the buses to be delayed for an extra 30 minutes at a random point on the line. Figure 5 shows the results for this case. We do not plot the departure lateness for the all hold strategy since its value (over 22 minutes on average) is significantly larger than the other strategies. Comparing strategy 3 with 4 and strategy 6 with 7 shows that the impact of bus tracking is more significant when one of the buses experiences a major delay, especially when there is a small number of connecting buses (N=2). Due to the high departure lateness associated with the all hold strategy, it provides the worst ratio to the lower bound. In this case, not holding (Strategy 2) and the forecasting strategies (Strategies 4, 5, 7 and 8) perform the best based on the total passenger delay criterion.

#### **INSERT FIGURE 5 HERE**

Figure 6 plots the results when the assumption of uniform spacing between stops is relaxed. In this set of experiments, the 24 major spots are randomly located along the route of 60

minutes. As the figure shows, the findings are similar to those of the uniform spacing assumption shown in Figure 3.

### **INSERT FIGURE 6 HERE**

We next tested the sensitivity as the variability in the delay changes. Figure 7 shows the results of this analysis. In this set of experiments, all parameters were set to their original basecase values except the delay variability ( $\sigma$ ) changes. Similarly, we assumed that the distance between the stops is 2.5 minutes. The figure shows results for four coefficients of variation of segment travel time ( $\sigma/2.5$ ). The number of connecting bus lines was set to five ( $N=5$ ). As expected, the figure shows the departure lateness and the fraction of passengers missing their connection increase as the variability increases. The interesting aspect of this plot is that the ITS-based dispatching strategies begin to significantly outperform the non-ITS based dispatching strategies as a ratio to the lower bound as the variability decreases since the forecasts become more accurate with less variability.

### **INSERT FIGURE 7 HERE**

We remark that we also tested the sensitivity of the above findings for numerous other values of the input parameters and found no difference in the results. The other values tested include a total scheduled trip length of 30 minutes, expected number of passengers on the bus when arriving to the terminal of 25 and 50 passengers, distance between major stops of 5 minutes,  $\alpha = .05$  and  $\alpha = 1.0$ .

## 5. CONCLUSIONS

Intelligent transportation systems have the potential for improving the performance of bus systems by providing improved connectivity between lines at timed transfer terminals. By relaying a bus location in real-time, and relaying information as to whether or not transferring passengers are on board, an informed decision can be made as to whether to hold or release connecting buses. Our review of ITS technologies shows that there exists technologies in the marketplace that can perform real-time control of timed transfer.

The potential benefits of such a system were estimated through simulation of timed transfer terminals with 2 to 10 connecting bus lines. Under the ITS strategies investigated, a bus is only held when a late arriving bus is forecast to arrive within a pre-set holding time. Without ITS, connecting buses are held up to the pre-set holding time automatically when other buses are late. As a consequence, ITS has the potential to reduce waiting time for passengers on the connecting buses without greatly increasing the number of missed connections. This hypothesis was borne out in our simulations. The results of the simulation analysis show that dispatching strategies using ITS can provide benefits in terms of reduction in passenger delay. The impact though of bus tracking is most significant when one of the buses experiences a major delay, especially when there is a small number of connecting buses. Furthermore, as the delay variability decreases the tracking-based dispatching rules begin to significantly outperform the non-ITS based strategies since the bus arrival time forecasts become more accurate.

It should be noted that in most of our simulations, average passenger delay is minimized when following the policy of holding until all buses arrive. This is obviously a simple and attractive policy that guarantees that every passenger makes his or her connection, and it does not require ITS. The drawback is that an all-hold policy performs very poorly when a major delay

occurs on one of the connecting lines. Another drawback is that downstream slack may not be sufficient to recover the schedule. It may be that a high level of performance can be achieved by asking drivers to radio in to their dispatcher when falling more than a set number of minutes behind schedule. This could then provide an exception to the all-hold policy, which would otherwise be employed.

As a side-issue, we discovered in our empirical analysis that delays over segments of bus lines are negatively correlated with lateness at the start of the segment. This indicates that buses that are behind schedule tend to catch up and buses that are ahead of schedule tend to slow down, counter to the phenomenon observed on short headway lines. It also appears that bus lines contain considerable slack. It may be that ITS would provide greater benefits if slack times were reduced. Moreover, the greatest benefit of ITS could come from enabling bus systems to meet their scheduled headway with fewer buses, which would be achieved through tighter schedules. This is the subject of ongoing research. Finally, the application of ITS in this particular problem might result in other benefits. For example, passengers may be able to better time their arrival to a stop if this information is posted.

## **ACKNOWLEDGEMENT**

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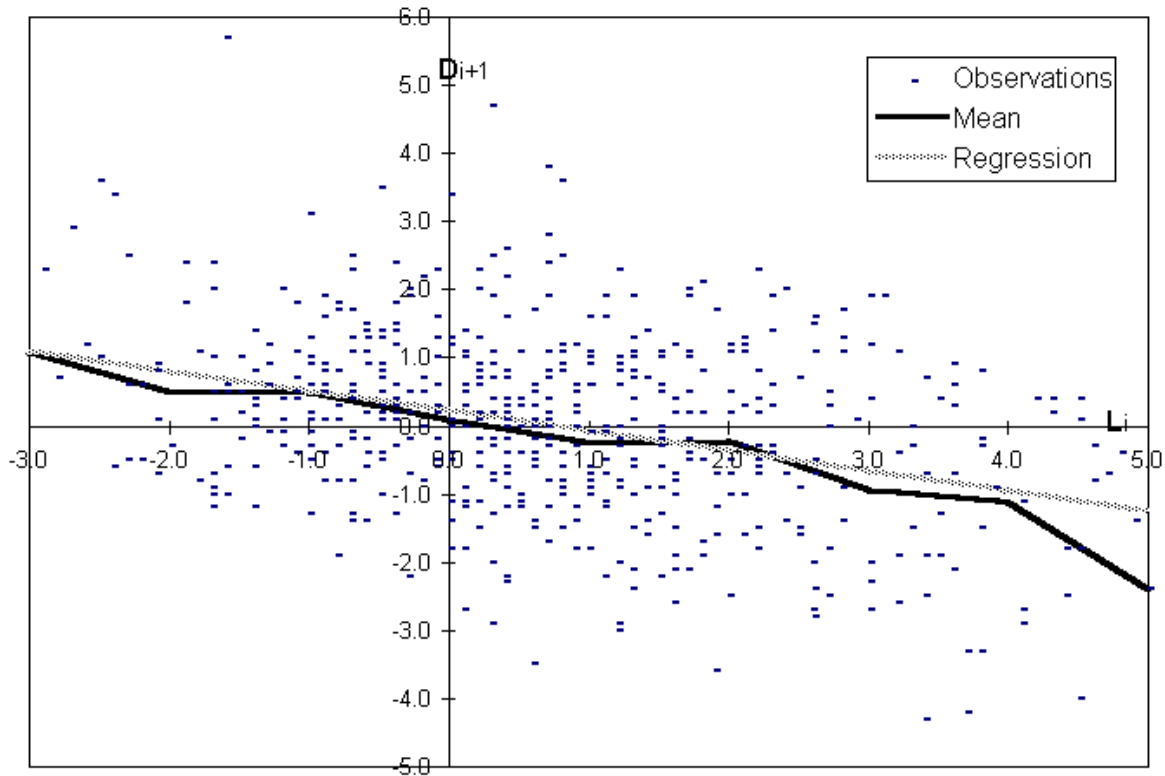
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**Table 1. Summary of Previous Studies**

<u>Authors</u>	<u>Random Variable</u>	<u>Distributions Function</u>
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, Travel Time	Normal
Lee and Shonfeld (1991)	Arrival Time, Travel Time	Normal, Gumbel
Hall (1985)	Lateness, Delay	Exponential
Talley and Becker (1987)	Lateness, Delay	Exponential
Jenkins (1976)	Travel Time	Normal
Andersson et al. (1979)	Travel Time	Lognormal
Turnquist and Bowman (1980)	Travel Time	Gamma
Seneviratne (1990)	Travel Time	Normal, Gamma
Wirasinghe and Liu (1995)	Travel Time	Gamma

**Table 2. Summary of Correlation Results**

Bus Line Number	$L_k$ vs. $L_{k-1}$		$D_k$ vs. $D_{k-1}$		$D_k$ vs. $L_{k-1}$	
	Correlation	t-value	Correlation	t-value	Correlation	t-value
26	.70	28.9	-.19	5.8	-.33	10.3
30	.66	27.4	-.26	8.3	-.34	10.6

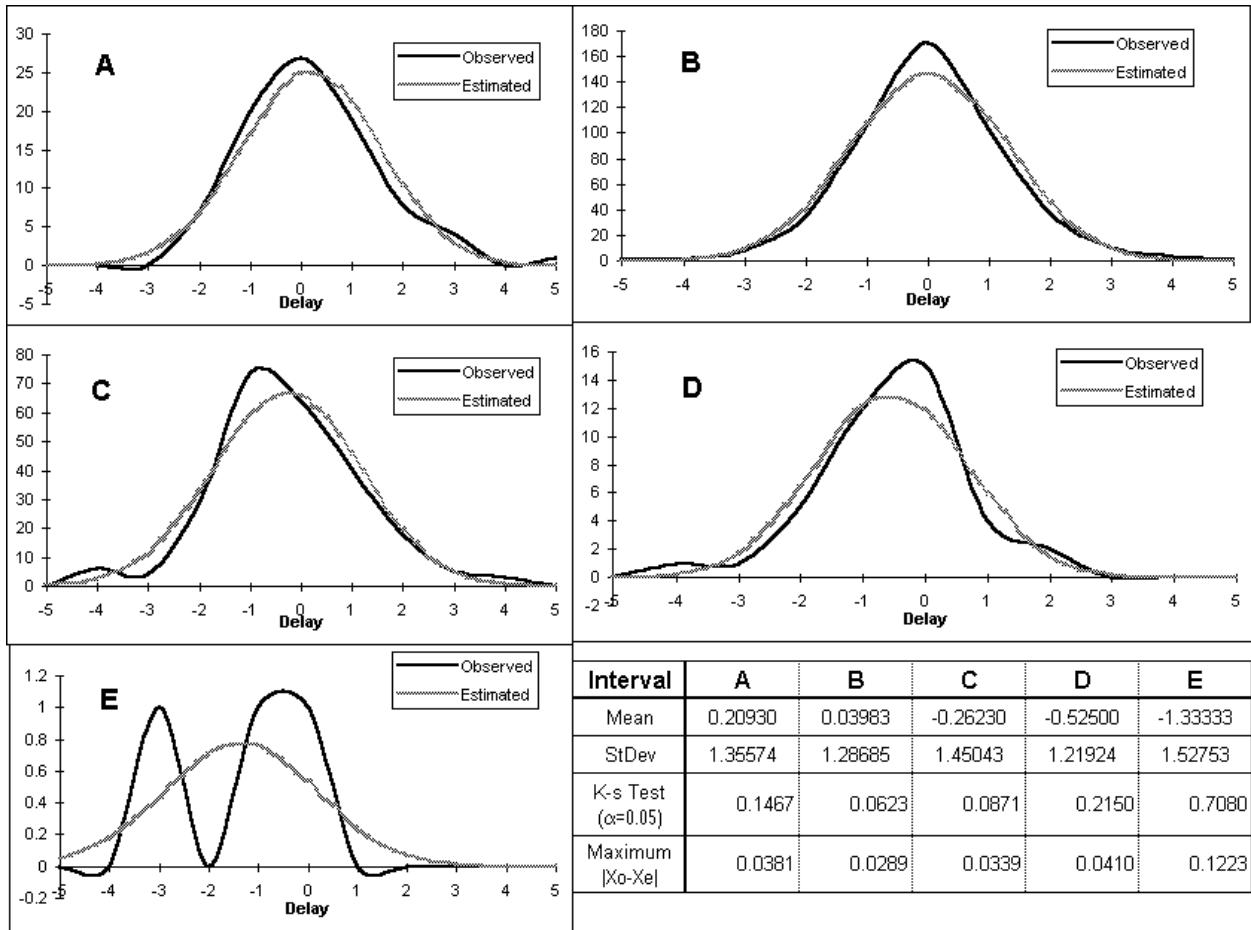


Regression Statistics	
Multiple R	0.3422914
R Square	0.1171634
Adjusted R Square	0.115662
Standard Error	1.2257286
Observations	590

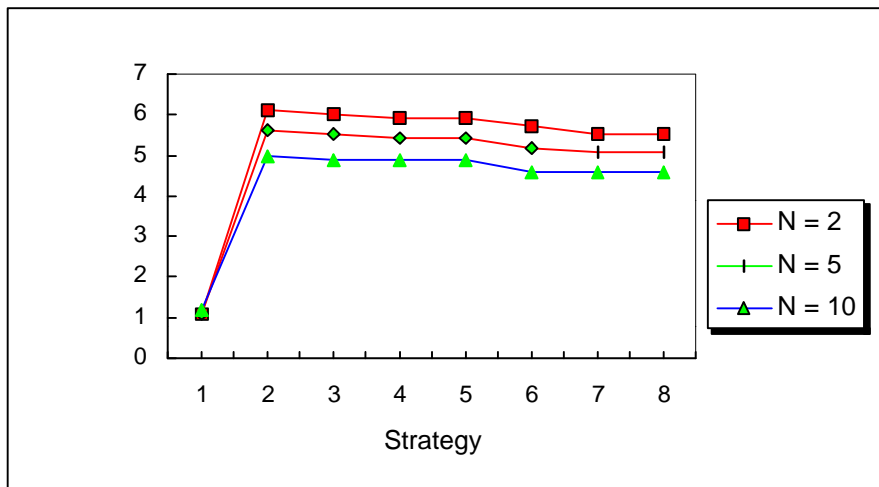
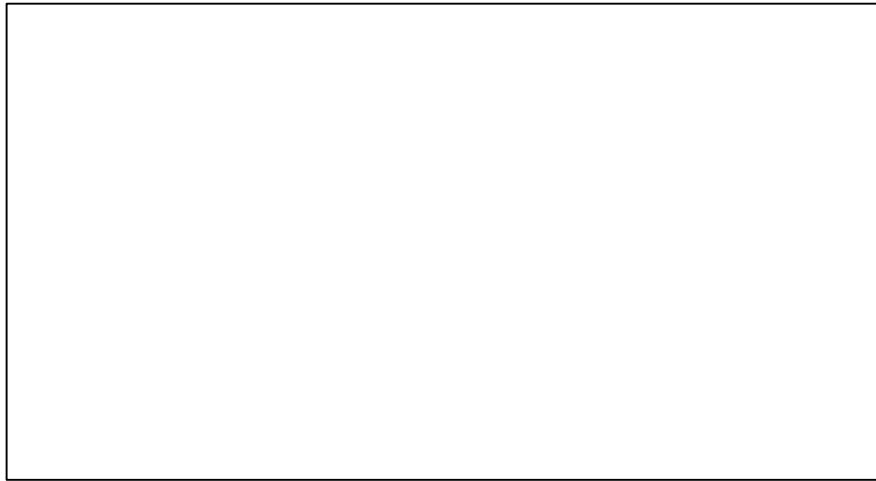
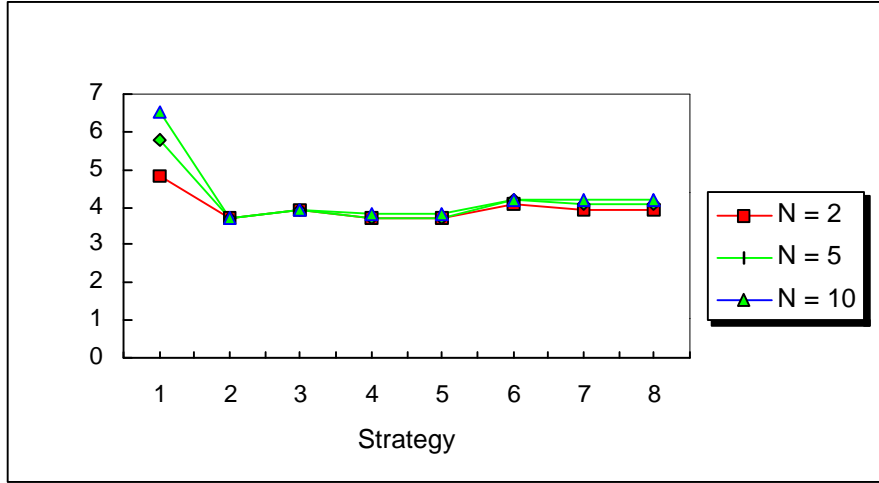
ANOVA					
	df	SS	MS	F	Significance F
Regression	1	117.240506	117.24	78.03	1.1644E-17
Residual	588	883.417477	1.5024		
Total	589	1000.65798			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
<b>Intercept (<math>\alpha</math>)</b>	<b>0.2336</b>	0.05500825	4.2466	3E-05	0.12555922	0.3416326	0.12555922	0.34163255
<b>X Variable 1 (<math>\beta</math>)</b>	<b>-0.29247</b>	0.03310823	-8.834	1E-17	-0.3574943	-0.227445	-0.3574943	-0.2274446

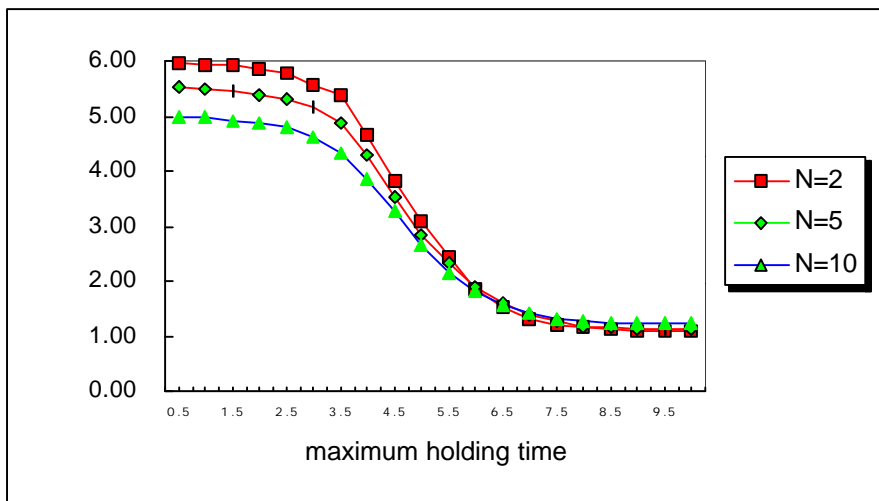
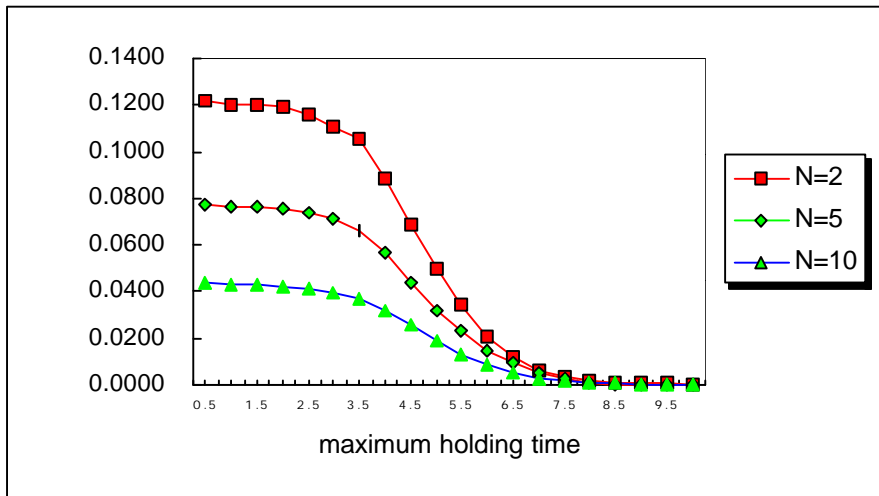
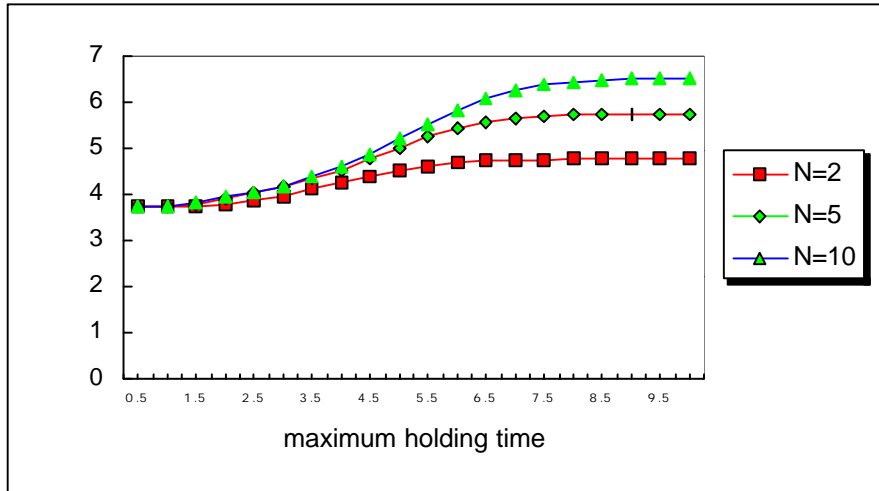
**Figure 1. Relationship Between Delay and Lateness from Previous Segment for Bus Line #30**



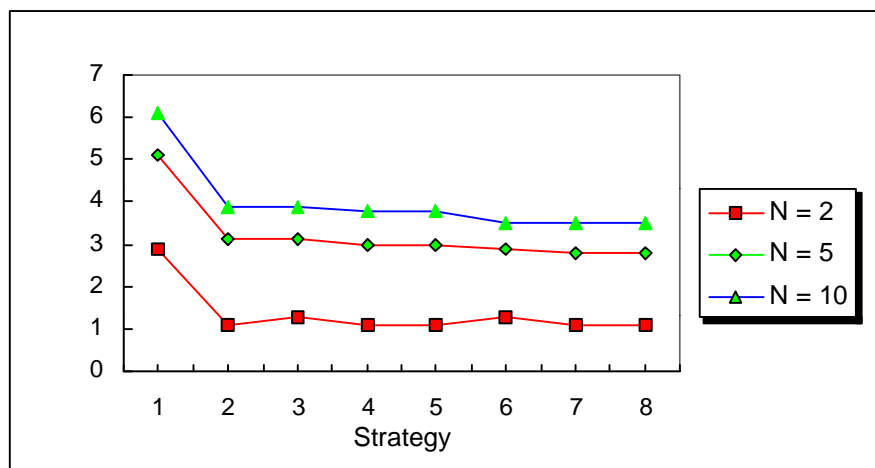
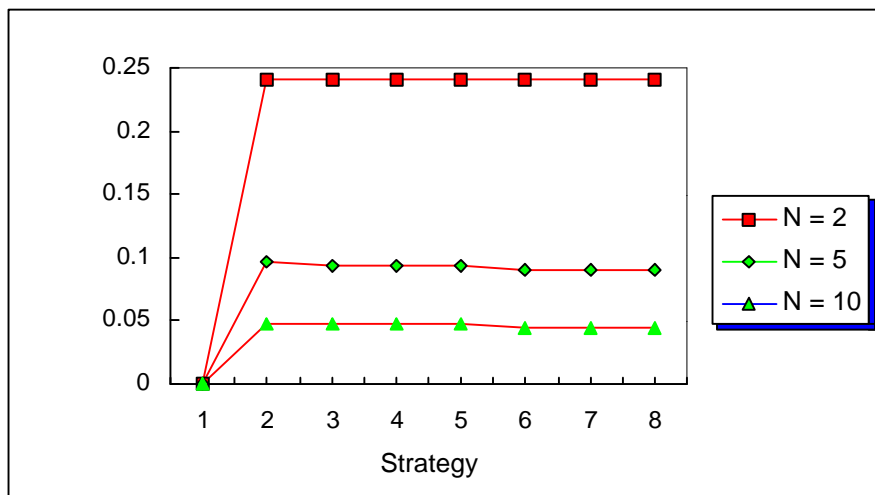
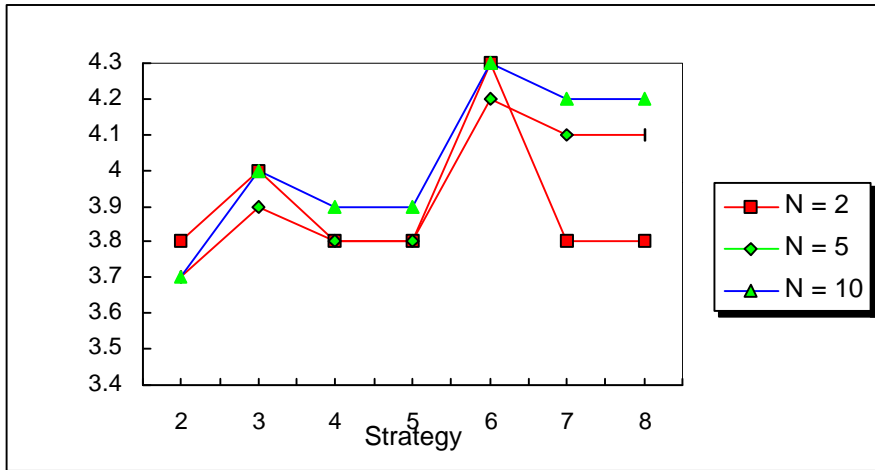
**Figure 2. Distribution of Delay for Given Lateness Intervals for Bus Line #26.**  
 (Range: A,  $(-\infty, -2]$ ; B,  $(-2, 0]$ ; C,  $(0, 2]$ ; D,  $(2, 4]$ ; E,  $(4, \infty]$ )



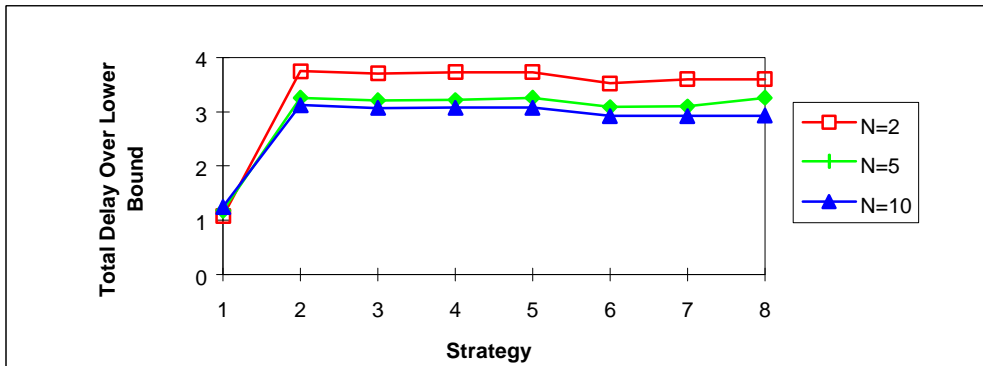
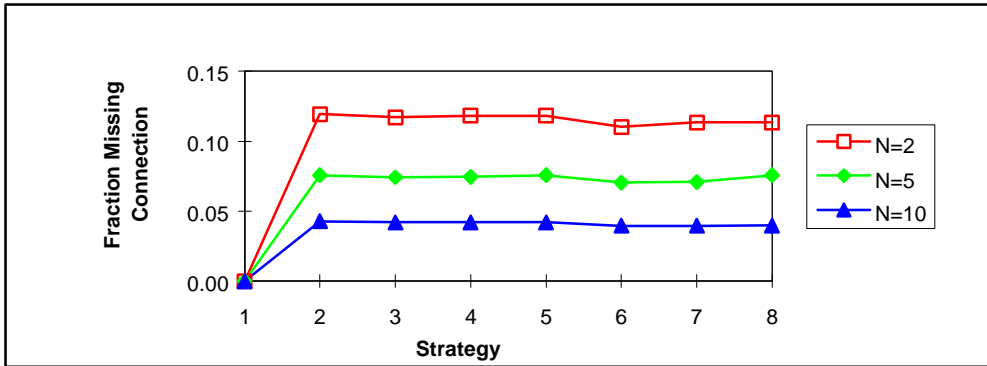
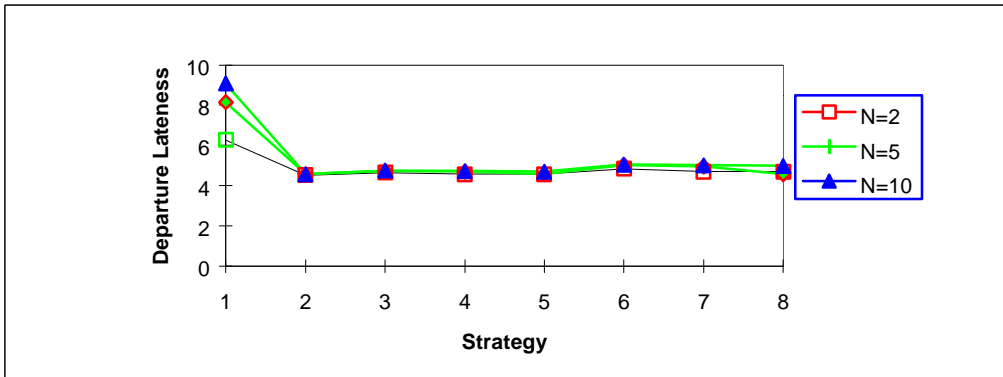
**Figure 3. Summary of Results for the Different Dispatching Strategies.**



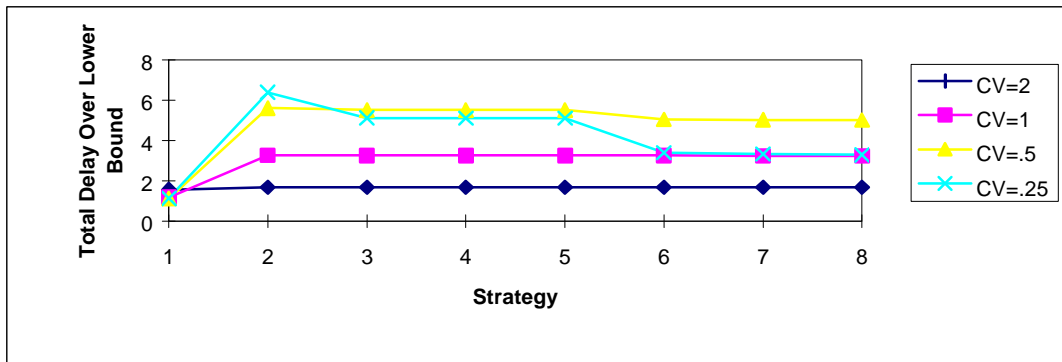
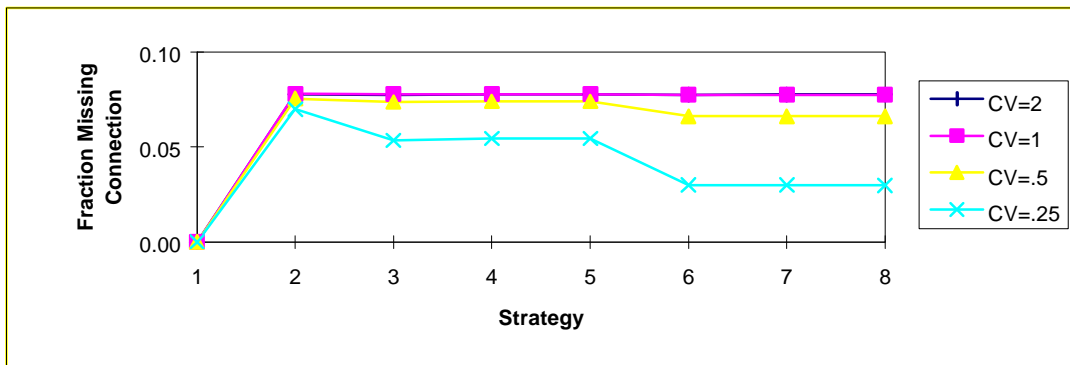
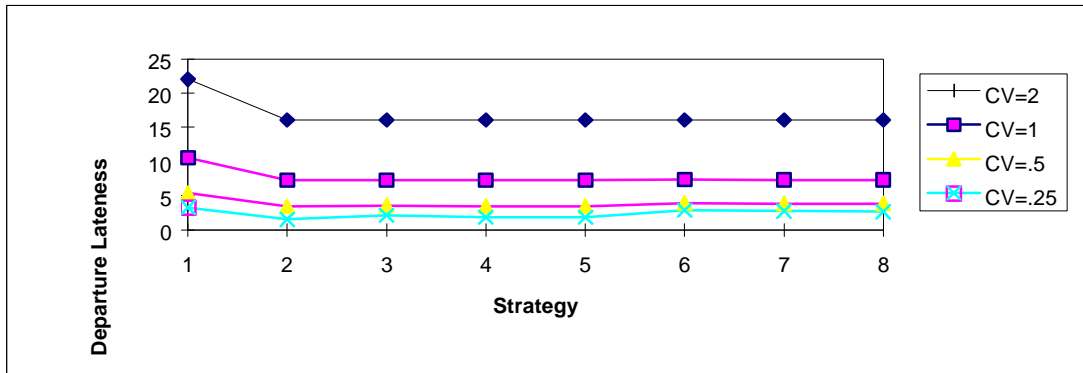
**Figure 4. Summary of Results for Forecasting and Hold Strategy as the Maximum Holding Time Varies.**



**Figure 5. Summary of Results When There is a 30 Minute Breakdown.**



**Figure 6. Summary of Results With Non-Uniform Spacing Between Stops.**



**Figure 7. Sensitivity of Results With Changes in Delay Variability**