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Evaluation of ITS Technology for Bus Transit Systems

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ABSTRACT

Recently, bus transit service providers have begun to adopt Intelligent Transportation Systems (ITS) technologies such as Global Positioning Systems (GPS) and Mobile Data Terminals. 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. We evaluate bus control strategies using ITS 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. For those strategies using ITS, we develop methods to forecast bus arrival times to a stop and the number passengers on board the bus. Results of a simulation analysis show that the ITS based strategies have the potential to improve connectivity between origins and destinations while reducing passenger waiting times.

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 is to minimize the cost of achieving a desired level of service or, alternatively, maximizing the service quality within a given budget. Metrics that are 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 PATH report: Diane Bailey and Randolph Hall, "The Impact of Intelligent Transportation Systems on Bus Driver Effectiveness, UCB-ITS-PWP-97-25, 1997) and simulation of transit networks with ITS capabilities.

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.

In terms of minimizing the average passenger trip time the ITS strategies outperformed the non-ITS based strategies for the randomly generated problem sets, though not for the OCTA dataset. Strategy #7, which does not preset the maximum holding time and determines it from minimizing the total waiting time among passengers currently at the stops and those forecasted to arrive before the bus arrives, was the best performing ITS based strategy in terms of minimizing the average passenger trip time. This strategy tends to balance the time saving for transfer passengers because of holding and delay for on-board or originating passengers at subsequent stops. This strategy provides the biggest advantage when:

- expected actual travel time is close to the scheduled travel time, and
- headway is large
- a large number of passengers patronize the route

Overall, it is disappointing that ITS did not provide larger time savings in our analysis. **A** fundamental reason is that in many situations it is optimal to do either of the following: (1) leave immediately, whether or not connecting buses have arrived (no hold), or (2) wait as long as possible until all connecting buses have arrived. These extreme alternatives require no communication and no-ITS. ITS is more beneficial in intermediate cases, where a connecting bus incurs a small delay, and it is more advantageous to wait for its arrival that to depart without the connecting passengers. These benefits must be weighed against the considerable cost of installing and maintaining a tracking and communication system. Though a cost-benefit analysis was not performed for this work, timed transfers alone do not seem to justify the installation of ITS.

The savings per passenger appear to be no more than 1 minute, which translates into annual time savings on the order of 500 to 2000 hours per bus. Savings of this magnitude may be sufficient to justify an ITS installation, with payback within a few years. More generally, the savings are highly site specific, and should be evaluated on a case by case basis, taking into account the factors described in this paper.

This report documents results of the simulation analysis along with background. An accompanying report documents the developed simulation model. The model has the capability to simulate wide-area transit networks. Results of the simulation analysis show that the ITS based strategies have the potential to improve connectivity between origins and destinations while reducing passenger waiting times.

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. In the transit industry, Global Positioning Systems (GPS) and Mobile Data Terminals 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. For example, through accurate tracking data, it might be possible to set vehicle schedules so that they more accurately match actual run times. In this, schedule slack can be eliminated where it is not needed, and schedule performance can be improved where more slack is needed. **As** a consequence, service commitments can be satisfied with fewer buses, at lower cost.

With the use of real-time information and bus control, connectivity between origins and destinations may also be improved while reducing passenger waiting times. Real-time control could facilitate tighter scheduling at transfer stops, reducing waits and vehicle costs while enabling people to make their connections. This report evaluates the use of ITS technologies on real-time control of buses. 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 are evaluated based on several performance metrics, including average passenger trip time, and average total passenger delay.

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 that account for 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 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 is very flexible 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 remainder of this report is divided into six sections. We first summarize the use of advanced technology for enhancing productivity in the transit industry. Next, we review the relevant literature in transit modeling. Third, the real-time control strategies with and without ITS are presented. Fourth, we describe how vehicle and passenger forecasting is implemented in the model. Fifth, the simulation analysis of usage of ITS for productivity enhancements is presented.

2. BACKGROUND ON BUS PRODUCTIVITY

Information technologies (IT) are widely used in American industry as a tool for increasing productivity and enhancing customer service. Productivity is generally defined as the ratio of output to input and, in the case of buses, can be viewed as the number of passengers or passenger-miles carried per hour of operation. Through the increased use of computers and other communication infrastructure, IT simplifies processing of information, increases the accuracy and speed of process control, and provides access to data that can make a company more responsive to market conditions.

In the transit industry, IT is available in the form of “Advanced Public Transit Systems” (APTS), a form of Intelligent Transportation Systems (ITS). APTS encompasses a wide range of technologies, including Automatic Vehicle Location (AVL), Automatic Passenger Counters (APC), Transportation Management Centers (TMC), Automated Fare Collection (AFC) and Advanced Vehicle Monitoring (AVM). These technologies provide the capability to continuously track vehicles, improve schedule adherence, and respond to breakdowns and emergencies. They also generate archived data, which can be used to evaluate rider-ship and on-time performance trends, which can in turn be used to improve service planning.

Methodolo–w

A survey was completed to document how technologies are being used to improve productivity within existing and planned implementations of APTS. The findings are based on interviews with agencies that are known to being using, or planning to use, APTS, along with interviews with all categories of transit agencies in California. The study sample consisted of public transit agencies located in the United States. These transit agencies were selected in two ways. First, we selected locations that were known to have, or were planning to implement Advanced Public Transportation Systems (APTS). Secondly, we attempted to contact all major transit agencies in California, independent of functionality, real or planned. The transportation agencies, both locally and nationally, were identified through national and local directories, research reports as well as various articles. As a follow-up to searching publications, Internet queries and interviews of staff at contacted agencies were also conducted to ensure that the list of transportation agencies and their respective locations was accurate, up-to-date, and complete.

Once agencies and their locations were identified, a list of contact names and telephone numbers was generated. These contacts were supplied by the identifying source, usually a publication or through the Internet. If no contact name or number was given, then the location's general information number found in a national directory was used as the point of contact.

The study called for the interviewee to be someone with knowledge of existing operations, planned operations, or daily performance. The ideal candidate would have management perspective as well as operational expertise. The person to be interviewed typically held the title of Director of

Planning or Director of Operations. However, due to the variety of locations contacted and the differing organizational structures, job titles varied. In the case of smaller agencies, those with fewer than 30 busses in operation often did not have these positions. In such cases, we screened the interviewee with sample questions or with a brief introduction, when possible, to test the person's knowledge and capability for answering our sample questions.

Interviews were conducted by telephone, and followed the interview guide located in Appendix B. In some cases, interviewees responded by fax with additional information after an initial telephone conversation. The questions were designed to determine the following:

1. Agency's level of technology, current and planned.
2. Motivating factors behind setting up or planning to set up advanced technologies
3. Usage, or planned usage, for the technology and the information that it generates.
4. Whether technology is being used as intended.
5. Aspects of bus operations that are most affected by technology.
6. Day-to-day use of advanced technologies.

The specific questions varied somewhat from location to location, depending on the technology planned or in use. For example, if the agency had no advanced vehicle locator system we did not ask questions concerning the use of tracking data. The interviews lasted between five and thirty minutes depending on the level of technology and availability of the interviewee.

We were able to reach 30 out of the 40 locations contacted, of which 77% agreed to participate (Appendix C). In some cases we were unable to reach a qualified person, due to either calls not being returned after multiple attempts (minimum of five), or not locating a knowledgeable person in the agency concerning our study questions.

Upon completion of data collection the results were grouped by level of planned and implemented APTS, for a listing of the APTS that we considered see Appendix **3.** The groups with planned APTS had at least one of the qualifying APTS planned for implementation. No determination was made for date of planned implementation, only that the process was underway for its deployment. Groups with implemented APTS qualified if they were currently operating one or more of the advanced technologies. We concentrated on Transportation Management Centers, Advanced Vehicle Locators, Vehicle Component Monitoring Systems and Automated Passenger Counters.

These results were both quantitative through multiple choice questions, including numeric responses, and qualitative through observational responses about APTS productivity. Other grouping of data was done by location. This grouping was necessary due to the variety of planned or real APTS deployment of the locations polled.

Findings

For analysis purposes, agencies were grouped according to their usage of APTS, based on the technologies they have in operation and the technologies they are planning to deploy. The groupings and number or locations polled are summarized below:

Group	*Description*	*Number*
1.	Locations with APTS that are planning on implementing more	11
2.	Locations with APTS that are not planning on implementing more	2
3.	Locations without APTS that are planning on implementing some	6
4.	Locations without APTS that are not planning on implementing any	4
	Total	23

Most of the locations interviewed believe that APTS is beneficial in some way to bus operations if not productivity directly. The majority of Group 1 and Group 2 agencies, greater than 80 percent, believed that they were providing a more efficient and safer service to the customer through the use of advanced technologies. However the major concern of the agencies, when using advanced technologies, was the extraction and useful analysis of the generated data. **As** the results of the study were compiled it became apparent that technology, such as advanced vehicle location and automated passenger counter, generated huge amounts of data. The resulting problems were having the technical staff and compatible software to extract and successfully use the data.

For Groups 1 through 3 productivity, scheduling, customer satisfaction, and security were the most often cited motivating factors for acquiring APTS (Table 1). However, when asked to scale the importance of these different factors fiom 1 to 5, customer satisfaction rated highest on average, followed by productivity, security and funding availability respectively (Table 1). Through data compilation it became apparent that most of the agencies were concerned about the perception of public transportation and felt that advanced technology was badly needed to keep up with rising customer standards.

Productivity was mentioned by 67% of the agencies in Groups 1 through 3 as a direct benefit of APTS, yet none had plans to measure improved productivity in the future and very few had completed productivity evaluations. In addition locations with APTS in operation several years had not yet measured productivity even though many of these locations were planning increased deployment of APTS. Study respondents reported that productivity increases in regards to bus operations included reduced emergency response times and increased scheduling efficiency.

The most common technology planned or in use is automatic vehicle location. Totally, 88% of the facilities surveyed either have or plan to have AVL as part of their transportation management system. This is nearly double the number of APTS when compared to other technologies such as automated vehicle maintenance or automated passenger counters.

Characteristics of Agencies Planning to Implement More APTS Eleven of the agencies studied currently have APTS or are planning to implement additional APTS. Of these agencies 72% cited productivity as a top priority for further implementation for APTS.

In questionnaire responses agencies considered productivity to be a direct result of implementing APTS. The data show that although productivity is a motivating factor for acquiring APTS, it has not been measured by agencies that currently have APTS. Even in this operating group that plans on acquiring more APTS to improve productivity, only two of the centers had completed a formal productivity evaluation and three others had some form of internal evaluation.

When questioned about the results of the APTS they have implemented, schedule adherence and efficiency are most often mentioned, followed by dispatching efficiency. The only negative effect of technology implemented is the inefficiency of the advanced vehicle monitoring system.

Table 1. Response to Scaled Questions

Ratina of Importance	Averaae
Importance to Purchase Tracking	
Customer satisfaction	4.50
Security	4.22
Productivity	4.17
Fundina availability	3.72
Component Monitoring	
Customer satisfaction	4.11
Productivitv	3.72
Fundina availability	3.72
Securitv	3.56
Automatic Pavment	
Customer satisfaction	4.75
Productivity	4.25
Security	3.94
Fundina availability	3.69

Table 2. APTS Effectiveness

Effectiveness of APTS Functions	Average
Schedule efficiency	3.88
Dispatching	3.88
Effort to create bus schedules	3.56
Reduction in on the road repairs/breakdowns	3.33
Bus maintenance	3.00
Amount of overtime/drivers wages	3.00
Fare collection	2.88

Agencies did not cite reduction in repairs and bus maintenance, as would be expected. Several locations reported no benefit fi-om the advanced vehicle monitoring technology. One location's maintenance department refused to use the technology because they were satisfied with the existing vehicular equipment. As another example a different location had shut the advanced vehicle monitoring system off because of repeated false alarms.

Most of these agencies, felt an urgent need for the Automated Vehicle Locator (AVL) system. This was a topmost priority for almost all agencies that did not employ AVL till now. The major reason behind acquiring AVL was revealed to be driver security. One agency also reported the kidnapping of one of their bus drivers as a motivating factor for implementing AVL.

Locations with deployed APTS also experienced difficulties in extracting information being generated by the new technologies. Data collection and analysis were major concerns of these facilities. The number of technical staff required to take full advantage of the technology was underestimated by these locations during implementation. The overwhelming amount of data lowered many agencies opinions on the effectiveness of APTS. The locations surveyed, however, were not dismayed by the difficulties they had encountered. The agencies felt that through complete staffing and training the results of the advanced technologies would improve upon their already satisfactory status.

Characteristics of Agencies that do not plan to Implement APTS Two locations polled currently have some advanced technologies integrated in their agency and do not plan on implementing more. These locations were satisfied with the results of the implemented technology.

The driving forces here mimic those of the previous section in that their motivations to acquire APTS were customer satisfaction, productivity, and security. Some of the difficulties became more apparent in locations where technology was already in operation. Problems such as under-staffing and data extraction were present here as well. Funding availability was also cited as a reason for not immediately implementing more APTS.

Although productivity was a concern in this group, no studies had been completed on the effects of the advanced technology on bus operations. The word efficiency was used to describe improvements that were hoped to improve bus operations, but the level of this efficiency had not yet been measured.

Characteristics of Agencies Planning First APTS Implementation Six locations do not have APTS in operation, but plan to implement APTS within the next five years. All of these agencies considered productivity to be a driving force behind acquiring advanced technologies. Other motivating factors were customer satisfaction and security. Only one of these centers was officially evaluated for productivity and one other had internal evaluations. None had plans to measure changes in productivity after new technology implementation. Most of these locations had similar goals, to locations who had already implemented APTS, of increasing efficiency in scheduling and routes, and to increase security, while providing the end customer with a better product.

Characteristics of Agencies Not Planning to Have APTS Four locations do not have or plan to have advanced technologies anytime in the near future. These locations were limited by funding availability and size. Smaller locations did not see the need for implementing software for small fleets. Another reason for not acquiring APTS was that they felt that the technology had not yet been successfully integrated into the bus system operations.

Characteristics of California Agencies Of the agencies studied in California 67% planned or already have implemented APTS. Of these locations many had reported financial constraints as the limiting factor for what APTS were to be acquired. Of the locations that were operating APTS no determining factors could be identified between agencies inside California as opposed to those outside of California.

Case Studies

Examples of how APTS technology is being used can be found in Atlanta, Georgia (MARTA) and at Metro King County, Washington. These facilities have integrated advanced technologies into bus operations. These locations are also experiencing the difficulties of integrating new advanced technologies into the public transportation industry.

MARTA is a large metropolitan agency with 700 busses. They have an advanced vehicle locator (AVL) system equipped with GPS technology. Although the system covers only 1/3 of the busses, they still see the benefits and difficulties of using the system. The agency is equipped with automated passenger counters (APC), automated transit information, operations software, and shares information with a traffic management center. The center has set up these systems with the motivation of moving busses more efficiently and safely. They feel that they have accomplished this goal in part.

Much like other agencies with AVL and APC, they are generating huge amounts of data that are difficult to extract and compile. These problems of data compilation are compounded by under-staffing and inadequate support fiom other divisions. Other departments feel that technology should reduce staff support, not increase it. Atlanta has seen the opposite, due to the needs of maintaining hardware and software, and processing the information generated. Despite these problems, Atlanta feels that their operations have improved due to APTS implementation but would improve more if the support were given to fully staff the facility. MARTA has seen an increase in rider-ship of 8% since implementation, though no studies have been completed to determine the cause. Thus, like all the other public transportation agencies studied, MARTA has never analyzed productivity due to the implementation of advanced technologies.

King County Metro is another large agency operating advanced technology. They have implemented APTS to cover their entire fleet of 1000 busses. They utilize the signpost/odometer method of AVL; GPS was not developed at the time of deployment. The agency also uses bus operation software, advanced communication, and a transportation management center to coordinate advanced technology functions.

The facility experiences the same problems of data management as other locations, but has the added problem of holes in the data being created by the signpost system. These gaps are created when a bus goes off route, resets from a different signpost, or malfunctions. The agency feels that advanced technology has aided in functions such as schedule adherence and schedule creation, but has fallen short of its potential due to the problems of data collection and reliability.

Security at Metro has improved due to the new technologies. The drivers can send silent alarms, and when accompanied by AVL, the system receives an immediate response. The dnvers feel more secure due the new technology but have reported some bad feelings of being watched for their entire route. However, they feel that the tradeoff of independence for security is well worth the sacrifice. This "big brother syndrome" was reported by several agencies and in all cases the interviewee stated that bus drivers feel the added security is worth the drawback.

Even though King County is fully operational, it has yet to measure the effects of the advanced technology on productivity. The interviewee stated that productivity changes are too difficult to measure. The agency repeated the themes of other agencies by saying advanced technology most affects scheduling, schedule adherence, and security.

Summary

The transit industry appears to be behind other industries in the application of information technology for improved productivity. Though many agencies cite productivity as a benefit, few if any have created methods to capture and apply data for productivity gains. **A** basic problem facing the industry is developing procedures for synthesizing meaningful results from massive amounts of data, and using these results as part of a productivity management strategy. For instance, methods are needed to:

- Analyze bus trajectories so as to optimize schedule times over trip segments and to set connection times at transfer points.
- Minimize boarding time through faster fare collection.
- Identify driving habits that help keep drivers on schedule
- Providing accurate feedback to drivers to help keep them on schedule.
- Analyze boarding patterns to determine where bus routes and stops should be placed.

The tremendous potential of ITS remains to be tapped in these areas.

3. RELATED RESEARCH IN PROBLEM AREA

There has been extensive research on controlling transit vehicles traveling along a single line with multiple stops. In routes providing frequent service (headways of 10 minutes or less), the objective in schedule control is largely to ensure consistency in headways (time separation between vehicle arrivals or departures). Customers on short-headway lines typically do not consult schedules before arriving at their stops, and therefore arrival patterns are reasonably stationary relative to the schedule. Second, as demonstrated in Osuna and Newell (1972), average waiting time increases with the square of the coefficient of variation in the headway (ratio of standard deviation to the mean). Completely random Poisson vehicle arrivals generate twice the average wait of deterministic arrivals. In fact, waiting time can be worse then the Poisson case, as vehicles on frequent lines have a tendency to bunch. Headways on very frequent lines are inherently unstable: when a bus falls slightly behind schedule, it tends to pick up more passengers, causing it to slow further, until it eventually bunches with the trailing bus (Newell, 1974; Barnett, 1974; Turnquist, 1978). This can be controlled, to some degree, by slowing down a trailing bus when it is catching up with the preceding bus. However, the added delay for passengers already on the trailing bus limits the applicability of this (and other) control strategies, except at the very start of lines.

The behavior of infrequent lines differs substantially from frequent lines. Customers generally do consult schedules, making arrival patterns non-stationary. Therefore, waiting time is not defined by the headway, but instead by the random deviations in the bus arrivals at the stop, along with the customer’s selected arrival time relative to the schedule. Finally, because late buses generally do not pick up additional passengers, schedules tend to be much more stable. As demonstrated in Hall et al. (1997), these attributes, combined with slack time inserted in the schedule, lead to schedule stability. Drivers also have an incentive to catch up to the schedule since most transit agencies penalize them for being excessively late. Thus, the delay in a segment is negatively correlated with the lateness at the start of the segment.

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. A positive correlation can occur when passengers do not consult a schedule prior to arrival (as usually occurs on low headway lines), which results in increased boardings when a bus falls behind schedule. **A** negative correlation can occur when the slack built into the schedule is sufficiently large so that the bus can catch up with schedule when it is running late.

There has been some work on optimizing holding and departure times at timed transfer centers. Hall (1985) 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). 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 (1991, 1992) simultaneously optimize headways and safety margins at a timed transfer terminal. Knoppers and Muller (1995) find that it is beneficial to coordinate transfers when the variability of the arrival times of connecting buses is low.

Lin et al. (1995) focus on developing bus dispatching criteria at various stops. **A** holding and stop skipping criterion 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 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. Other research in the holding problem where transfers are not considered includes the work by Osuna and Newell (1972), Newell (1974), Barnett (1974, 1978), Koffman (1978), and Abkowitz (1986).

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 concludes that ITS will lead to drastic changes in the way bus performance is measured. 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.

Our work differs from the previous research on transit modeling in several aspects. We analyze strategies that make 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. In addition to taking into account the current status of the transit system, the analyzed strategies ***forecast*** future states of the system.

An important aspect of modeling bus systems is the probability distribution for travel time along bus line segments. Different probability distributions for the travel time and arrival time random variables have been used in past studies. Most studies used a skewed distribution such as lognormal or gamma because of driver incentives to stay close to, but not ahead of, schedule. Some authors select the probability distribution based on empirical studies (e.g., Turnquist, 1978; Andersson et al., 1979; Talley and Becker, 1987; Guenthner and Hamat, 1985; Seneviratne, 1990; Strathman and Hooper, 1993) while others based their selection on model simplification (e.g., Hall, 1985; Bookbinder and Desilets, 1992; Wiransinghe and Liu, 1995).

Past studies indicate that there are two categories of passengers who board the bus: those who are aware of the scheduled arrival time and those who are not aware (Barnett, 1974; De Pirey, 1971). Aware passengers time their arrival at a stop according to the bus schedule. Unaware passengers come randomly to a stop, thereby having to wait for a longer duration of time on average. Okrent (1974) found that a headway of 12 to 13 minutes marks a transition period, where a much greater fraction of people is aware of the schedule. Similar results were obtained 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 Tumquist (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 declines 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. Similar arguments can be found in Turnquist and Bowman (1980, 1981).

In terms of boarding and alighting times, Kraft (1977) proposed the usage of a 2-Erlang distribution. Andersson et al. (1979) and Andersson and Scalia-Tomba (1980) use a gamma distribution. Turnquist and Bowman (1980) assume a normal distribution. In a simulation model analyzing on-time performance, Seneviratne (1990) referred to a high density stop as one which usually attracts a large number of passengers boarding or alighting. The number of boardings and alightings was simulated using normal and Poisson random variables for high and low density stops, respectively. We build from all the above observations in our simulation model.

4. BUS HOLDING STRATEGIES

This section presents seven strategies for releasing buses from a stop. We assume in all cases that when a bus arrives early at a stop, it will wait at least until its scheduled departure time before proceeding. At transfer stops, the bus may be held additional time so that passengers on other buses have a better chance of making connections. The seven strategies are defined by the information used, holding criteria and implementation, as follows:

Information Used

- Schedule for connecting buses at the stop
- Whether or not the connecting bus has already arrived at the stop
- Forecasted arrival time for connecting buses
- Forecasted number of transferring passengers on connecting buses
- Forecasted number of boarding passengers at subsequent stops

Holding; Criteria

- Whether or not forecasted arrival time for connecting bus is within time window
- Whether or not number of connecting passengers exceeds minimum
- Whether or not total waiting time for passengers already on bus and those connecting will decline if bus is held

Implementation

- Do not hold
- Hold indefinitely (until connecting buses arrive)

- Hold up to maximum time

Table 3 outlines seven holding strategies, which are defined by different combinations of the above attributes (see the Appendix for mathematical expressions for the different holding strategies). Strategies 1 – 3 do not require ITS technologies. Strategies 1 (No Hold) and Strategy **2** (All Hold) are two extremes relative to favoring passengers already on holding buses versus passengers on connecting buses. Strategy 3 falls between these extremes by placing upper bounds on holding time. Strategies 4 - 7 require ITS technology and forecasted arrival times for connecting buses. Strategies 5 – 7 additionally require forecasted passengers, and Strategies 6 and 7 additionally account for the net change in waiting time due to holding. Strategy 6 only considers the local impact where the bus is being held, whereas Strategy 7 also accounts for changes in waiting downstream from the stop. In addition, Strategies 6 and 7 do not preset the maximum holding time. Instead, the maximum is determined from minimizing the total waiting time among passengers currently at the stops and those forecasted to arrive before the bus arrives.

To allow for flexibility in modeling different types of stops, a different control strategy can be used in each stop along the bus route. The selected control strategy depends on numerous factors including 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.

5. FORECASTING METHODS

Some of the holding strategies require a forecast on bus arrival times and the number of passengers on the bus. In the presence of a bus tracking system, arrival times can be forecasted based on a bus' current location. 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 are not identical, the revised forecast at departure can be different from the one sent on arrival.

Consistent with studies by Turnquist (1978) and Strathman and Hopper (1993), we assume a lognormal distribution for actual travel time. We define the parameter $\gamma_{i,k}$ as the ratio of expected actual travel time to scheduled travel time:

$$E(AT_{i,k}) = \gamma_{i,k} ST_{i,k}$$

where

$AT_{i,k}$: actual travel time from stop k-1 to stop k for bus line i

$ST_{i,k}$: scheduled travel time from stop k-1 to stop k for bus line i

We will refer to segment k as the portion of the bus route that connects stop k-1 to stop k. The term $(1-\gamma_{i,k})$ represents the slack as a proportion of scheduled time in segment k for bus line i. Analyzing data from Los Angeles County, Hall et al. (1997) found the slack to be on the order of .25. The actual travel time on segment k is then assumed to be a lognormal random variable with mean $E(AT_{i,k})$ and variance $\sigma^2_{i,k}$.

We next describe two different forecasting methods for bus arrival and departure times at a stop. The two methods differ on whether or not early departure from a stop is allowed. The forecasting methods assume that a simple control strategy is executed at intermediate stops or, if not, that the effects of the control strategy are captured in a simple probability distribution for travel time, which is independent of departure time from a stop. The method also assumes that it is feasible for a bus to depart as soon as it arrives if it is behind schedule (forecasts are easily generalized to a fixed time translation). Terminology is defined as follows:

$AA_{i,k}$: actual arrival time to stop k for line i

$AD_{i,k}$: actual departure time from stop k for line i

$SA_{i,k}$: scheduled arrival time to stop k for line i

$SD_{i,k}$: scheduled departure time from stop k for line i

$FA_{i,k,k+n}$: forecasted arrival time to stop k+n for line i made at stop **k**

$FD_{i,k,k+n}$: forecasted departure time from stop k+n for line i made at stop k

$f_{i,k}(t)$: probability density function of actual travel time on segment **k** for line i

We define the forecasted arrival and departure time as the following expectation:

$$FA_{i,k,k+n} = E(AA_{i,k+n} | AD_{i,k})$$

$$FD_{i,k,k+n} = E(AD_{i,k+n} | AD_{i,k})$$

Scenario 1: early departure **is** *allowed*

The forecasted arrival time is simply the actual departure time from the previous stop plus the expected travel time:

$FA_{i,k,k+1} = AD_{i,k} + E(AT_{i,k+1})$

The forecasted departure time is equal to the forecasted arrival time.

$FD_{i,k,k+1} = FA_{i,k,k+1}$

The forecast arrival and departure times for stops greater than k+1 can be made by iteratively using the following equation.

$FD_{i,k,k+n} = FA_{i,k,k+n} = FD_{i,k,k+n-1} + E(AT_{i,k+n})$

The variance of both the actual arrival and departure times to stop k+n when the bus is currently at stop k is given by $\sum_{t=k+1}^{k+n} \sigma_{i,t}^2$ (i.e. the summation of the variances of the actual travel time for all the segments between stops k and k+n). This variance relationship holds because we are assuming travel times on the segments are independent random variables.

Scenario 2: early departure is not allowed

Although a bus may arrive to a stop ahead of schedule, it cannot be dispatched to depart ahead of the scheduled departure time when early departure is not allowed. Therefore, the forecasted departure time is not equal to the forecasted arrival time in this scenario. Similar to before, the forecasted arrival time at the next stop is the actual departure time from the previous stop plus the expected travel time:

$$FA_{i,k,k+1} = AD_{i,k} + E(AT_{i,k+1})$$

Since the actual departure is not allowed to be earlier than the scheduled departure time, the actual departure time ($AD_{i,k+1}$) at the next stop is the maximum of the actual arrival time and the scheduled departure time:

$$AD_{i,k+1} = \max(AA_{i,k+1}, SD_{i,k+1})$$

The forecasted departure time is given by the following equation

$$FD_{i,k,k+1} = E(AD_{i,k+1} \mid AD_{i,k}) = SD_{i,k+1} \int_{AD_{i,k}}^{SD_{i,k+1}} g_{i,k+1}(t)dt + \int_{SD_{i,k+1}}^{\infty} t g_{i,k+1}(t)dt$$

where $g_{i,k+1}(t)$ is the probability density function of $AA_{i,k+1}|AD_{i,k}$, which is $f_{i,k+1}(t)$ shifted by $AD_{i,k}$.

The variance of the actual departure time can be used to derive the forecast for subsequent stops and is given by the following equation:

$$\begin{aligned} Var(AD_{i,k+1} \mid AD_{i,k}) &= E(AD_{i,k+1}^2 \mid AD_{i,k}) - E^2(AD_{i,k+1} \mid AD_{i,k}) \\ &= SD_{i,k+1}^2 \int_{AD_{i,k}}^{SD_{i,k+1}} g_{i,k+1}(t)dt + \int_{SD_{i,k+1}}^{\infty} t^2 g_{i,k+1}(t)dt - FD_{i,k,k+1}^2 \end{aligned} \qquad (1)$$

To forecast the arrival and departure times for stop k+2, when the bus is at stop k, the following equations can be used.

$$FA_{i,k,k+2} = E(AA_{i,k+2}) = E(AD_{i,k+1}) + E(AT_{i,k+2}) = FD_{i,k,k+1} + E(AT_{i,k+2})$$

$$FD_{i,k,k+2} = E(AD_{i,k+2} \mid AD_{i,k}) = SD_{i,k+2} \int_{AD_{i,k}}^{SD_{i,k+2}} g_{i,k+2}(t)dt + \int_{SD_{i,k+2}}^{\infty} t g_{i,k+2}(t)dt$$

where $g_{i,k+2}(t)$ is the probability density function of $AA_{i,k+2}|AD_{i,k}$. The variance can be calculated as in Eq. 1, substituting density function $g_{i,k+2}(t)$ for $g_{i,k+1}(t)$, and increasing other subscripts accordingly.

The arrival time at stop k+2 equals the departure time at stop k+1 plus the travel time from stop k+1 to stop k+2. These two random variables are independent, and therefore the variance of $AA_{i,k+2}|FD_{i,k,k+1}$ equals $VAR(AD_{i,k+1}|AD_{i,k}) + \sigma^2_{i,k+2}$. The mean Of $AA_{i,k+2}|FD_{i,k,k+1}$ is then $FD_{i,k,k+1} + E(AT_{i,k+2})$. As an approximation, we assume that $g_{i,k+2}(t)$is lognormal.

We can iteratively use the approximation method to forecast the arrival and departure time at stop k+n when the bus is at stop k:

$$FA_{i,k,k+n} = FD_{i,k,k+n-1} + E(AT_{i,k+n})$$

where $FD_{i,k,k} = AD_{i,k}$

$$Var(AA_{i,k+n} \mid AD_{i,k}) = Var(AD_{i,k+n-1} \mid AD_{i,k}) + \sigma^2_{i,k+n}$$

where $Var(AD_{i,k}) = 0$

$$FD_{i,k,k+n} = SD_{i,k+n} \int_{FD_{i,k,k+n-1}}^{SD_{i,k+n}} g_{i,k+n}(t)dt + \int_{SD_{i,k+n}}^{\infty} t g_{i,k+n}(t)dt$$

$$Var(AD_{i,k+n} \mid AD_{i,k}) = E(AD^2_{i,k+n} \mid AD_{i,k}) - E^2(AD_{i,k+n} \mid AD_{i,k})$$
$$= SD^2_{i,k+n} \int_{FD_{i,k,k+n-1}}^{SD_{i,k+n}} g_{i,k+n}(t)dt + \int_{SD_{i,k+n}}^{\infty} t^2 g_{i,k+n}(t)dt - FD^2_{i,k,k+n}$$

We now test the error of the forecasted arrival and departure times using the above described approximation technique as a function of the slack on the schedule. We are concerned with the sensitivity of the forecasts to y since this parameter determines the relationship of the truncated point (scheduled departure time) and the actual arrival time distribution. When y is small meaning there is a lot of slack in the schedule, the majority of the actual arrival time density distribution is on the left side of the scheduled departure time. Hence, the actual arrival time will be much less than the schedule, while the actual departure time will be slightly larger than that from the schedule and approaches the schedule as y asymptotically approaches zero. When γ is a large number, most buses arrive behind schedule, i.e. majority of the actual arrival time density distribution is on the right of the scheduled departure time. Both the actual arrival time and departure time are much greater than the schedule. Also, they are almost identical. The least intuitive and difficult forecasts to obtain are the cases when there is no or very little slack in the schedule.

We test our approximation over the three possible cases as outlined above with $\gamma = .2$, 1, and 2. The results are shown in Tables 2, 3, and 4. We assume ten stops in our simulations. The actual travel times on each segment where sampled from a lognormal distribution with expected travel time of 2.5 minutes and standard deviation of 1.5 minutes. These values are representative of bus segments in Los Angeles County (Hall et al., 1997). In each table, two sets of results are provided. The first set of results show the mean absolute difference between the forecasted and actual arrival times averaged over 100 runs as the bus moves along its route. For example, the entries in the first row represent the forecasts made at the first stop. The second set of results show the mean absolute difference between the forecasted departure time and the actual departure time. As the tables show, the forecasts made by the above approximation are relatively close to the actual values. As expected, in all cases the forecasts are more accurate (i.e., closer to actual values) as the bus gets closer to the stop. **As** we outlined earlier, the results show that the least accurate forecasts are when there is little or no slack ($\gamma = 1$) since for the extreme values of gamma (i.e., $\gamma = .2$ or **2)** the actual departures will be close to the scheduled departures for a small gamma and actual arrivals will be close to the actual departures for a large gamma.

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. Our passenger forecast method is based on using the control logic at subsequent stops. We describe the approach used in the model next.

$$FP_{i,k+1}=P_{i,k}*C_{i,k}+O_{i,k}+TP_{i,k}$$

where:

$FP_{i,k}$	The forecast number of passengers on bus line i at stop **k**
$C_{i,k}$	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 passengers on board the bus at stop **k** on line i

Our estimate for TP_{ik} is as follows.

$$TP_{i,k} = \sum FP_{j,k} * C_{j,i,k} * I_{j,i}$$

where:

$FP_{j,k}$ The forecast number of passengers on line j at stop k

$C_{j,i,k}$ The fraction of people transferring from line j to line i at stop k

$I_{j,i,k}$ Equals 1 if the forecasted arrival time of line j is before the forecasted arrival of line i at stop k ($FA_{jk} < FA_{ik}$)

6. SIMULATION ANALYSIS

Model Description

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 primary evaluation criterion is the average passenger trip time, where trip time is defined to be the time a passenger leaves the bus network (i.e., the passenger's actual arrival time at their final destination) minus the time the bus that the passenger initially boards is *scheduled* to arrive. We base the definition of the trip time on the scheduled bus arrival time instead of the actual arrival time of the passenger because we assume arrival in relationship to schedule. Note that included in the trip time is the waiting time of the passenger at all intermediate stops.

Another evaluation criterion is the total passenger *delay*. The definition of delay depends on the passenger type. For passengers already on board, passenger delay is the difference between actual bus departure time and the scheduled departure time, minus the bus lateness at the previous stop. The lateness is subtracted to insure the delay is not double counted for multiple stops. The passenger delay is then the maximum of this value and zero. For originating and transfer passengers, the delay is defined to be the maximum of zero and the difference between the actual departure time and the scheduled departure time. For originating passengers, we use the passenger's scheduled departure time if they arrive either early or on-time. If the passenger arrives late, we use the scheduled departure time of the next bus to arrive. This ensures that we do not penalize the system for passengers missing their bus because of passenger late arrival. For transferring passengers, the scheduled departure time is for the bus line the passenger is coordinated to meet irrespective of the passenger's actual arrival time to the stop. In this case, the majority of the delay penalty for transferring passengers is for passengers missing their connection.

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 from a lognormal distribution with mean $E(AT_{i,k})$. Consistent with the simulation model of Seneviratne (1990), we assume that the number of passengers that arrive between schedule bus departures is Poisson distributed. Based on the observations of Bowman and Turnquist (1981), the arriving passengers are randomly categorized into aware and unaware passengers. The arrival time for each unaware passenger is simulated as a uniform random variable over the interval between scheduled departures. The arrival time for aware passengers is simulated as a normal random variable with a mean of one minute before the bus is scheduled to arrive at the stop.

The boarding times of the passengers are modeled as a Gamma random variable. Debarking and boarding take 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. Passengers that arrive during a holding period (after initial boarding and debarking) are accounted for separately.

The model forecasts bus arrival times and the number of passengers on board for stops in ITS scenarios. The forecasting techniques used in the model are based on the approaches outlined in Section 4.

Experimental Design

Bus networks are defined by numerous factors, including number of passenger boardings, distribution of arrival times, amount of slack in the schedule, number of transfer passengers, headway of buses, etc. To treat all of these parameters as exogenous controllable variables would create so many alternatives that meaningful comparisons of the performance measures would be virtually impossible. The focus of this experimental design is to study the impact of the various control strategies on the average passenger trip time as a function of the parameters y (assumed constant for all segments), H (bus headway), and N (number of connecting bus lines at a transfer station). Hence, these experiments are designed to provide a guideline for selecting appropriate holding strategy for some specific system parameters.

The base case of the sensitivity study is $y = 1$, $H = 60$, and $N = 5$. When one of the three factors is studied, the other two factors are set at their base case values. We next describe the other characteristics of the bus network that are held fixed for the purpose of this analysis.

The actual travel times on each segment where sampled from a lognormal distribution with expected travel time of 2.5 minutes and standard deviation of 1.5 minutes. These values are representative of bus segments in Los Angeles County (Hall et al., 1997). Consistent with previous studies, we assume that **2** passengers, on average, arrive during a headway at a stop, and that 50% are “aware” of schedules. The mean boarding and debarking times are set to 4.2 and 2.1 seconds, as proposed by Koffman (1978).

Each bus line has 12 stops in total, and stop 6 acts as a timed transfer station where all N lines coverage. A center location is selected for timed transfer so that the effect of holding on passenger waiting times at subsequent stops can be evaluated. All stops except for the timed transfer stop (stop 6) use a no hold strategy with no possibility of early departures since these stops have no timed passenger transfers. At stop 6, each passenger has a .50 probability of continuing on the bus and .50 probability of transferring with equal probability allocated to each connecting bus. Here, we assume that there is equal probability that passengers will continue their trip along the original bus line or transfer to other lines. Also, transfer passengers are assumed to transfer between busses with equal probability.

Different holding strategies are evaluated at the timed transfer stop only. Preliminary experimentation was used to determine the best holding parameters for strategies 3-5. The experiments showed that in most scenarios a maximum holding time of 3 minutes minimized the average trip time. In comparing the different holding strategies for a given scenario, we set the input control parameters for strategies 3-5 at the values that minimize the average passenger trip time.

<u>Experimental Results</u>

Figure 1 shows the average passenger trip time as a function of y, holding the scheduled travel time constant, with H = 60 and N = 5. As expected, the passenger trip time decreases with a lower y since system performance should improve as the expected travel time declines. For all values of γ shown, Strategy **7** performs best, especially for y in the vicinity of 1. If ITS technologies are not available, an all hold strategy is better than a no hold strategy. When γ is small, there is no significant difference among strategies.

In the experiments the only difference in the control logic is applied at the transfer station (Stop 6). Hence, the primary differences in the trip time is the delay incurred by the passengers at stop 6 and the subsequent delay at downstream stops due to holding the bus at Stop 6.

Figure 2 plots the total passenger delay at the transfer station (Stop 6) and Figure 3 plots the total passenger delay at the subsequent stops (Stops 7-12). From these plots, we can see that the all hold strategy provides shorter delay at stop 6 by sacrificing performance from stop 7 to 12 while the no hold strategy minimizes the delay for the subsequent stops. The overall gain or loss in system performance is determined by a tradeoff between these two delay components: time saving for transfer passengers because of holding and delay for on-board or originating passengers at subsequent stops. Strategy 7 accounts for these two parts of delay and attempts to achieve a global optimum.

We next study the effect of headway on system performance under the different holding strategies (Figures 4, 5, and 6). **As** expected, when headway is small there is no significant difference among the strategies. Otherwise, the global optimized strategy **7** is again the best performing strategy. The benefit is most significant when the headway is large. Another interesting observation is that for all strategies except strategy 2 (all hold), system Performance gets worse when headway increases. It can be intuitively explained that for bus lines with high headway, a delay related to missing a connection is expected to be longer.

Figures 7, 8, and 9 show the system performance measures as a function of the number of connecting buses, N. When N increases, an all hold strategy becomes the worst performing strategy since it does not make sense to hold all the connecting bus lines for just one late bus.

For a small N, a no hold strategy is the worst performing strategy since in this case it is beneficial to wait for all of the buses to arrive. Again, Strategy 7 attempts to balance the tradeoff between these two rules in determining the dispatching time.

Orange County Analysis

In addition to testing the control rules on a generic bus network, we evaluated the control rules on a portion of the Orange County transit service. All major stops for bus lines 47, 49, and 205 were included in the model. These lines were selected because they currently are being equipped with GPS receivers. Also, all lines connecting with lines 47, 49, and 205 were included in the model. The complete list of all simulated lines is contained in Table 5. Note that in total 96 different bus routes were simulated including both directions.

Table 6 shows the complete list of stops that were included in the model. In total 107 stops were simulated. Table 7 lists the connecting bus lines at each transfer stop.

The scheduled arrival times used in the simulation analysis were based on the published scheduled times. Thus, the scheduled travel time on a segment was set to be the difference between the scheduled arrival times between consecutive stops. The actual travel times were based on the models developed in Section 4 with $\gamma = 1$.

The expected number of boarding passengers at each stop was set to 2. This number was based on evaluating Orange County boarding data. For example, for the 2^{nd} Quarter in 1996 bus route 47 had a total of 106,450 boardings. During this period, this route made around 5658 runs making nine major stops for each run. At each transfer stop, the probability of transferring was set to be 30% of the probability of continuing. This estimate was based on taking the ratio of the total number of transfer requests over the total number of boardings for the 2^{nd} Quarter in

1996. Given a passenger requested a transfer, they had equal probability of transferring to any given line. Finally, a passenger has equal probability of departing at any stop.

The results based on 50,000 minutes of simulation are as follows.

	STRATEGY					
	1	3	4	5	6	7
Expected Passenger Trip Time	45.3	46.3	45.5	45.3	45.4	45.3

Strategy **2** is not listed since with many transfer stops the system becomes unstable with an “all hold” control rule. As the results show, there is no difference in the expected trip time between the rules except for Strategy 3. This strategy performs the worst since it does not take into account any bus arrival and passenger forecasts. Since the input data for the Orange County model contains limited passenger transfers, it is not advantageous to simply hold the bus a fixed amount of time neglecting the forecasts. The forecast based strategies are essentially performing similar to a no-hold policy since the forecasts show that there are limited transfers.

7. CONCLUSIONS

A simulation model of a wide-area transit network was developed to evaluate various real-time control strategies with ITS versus those without ITS. Two levels of ITS were considered: (1) system with centralized tracking and (2) system with information on connecting passengers, as well as centralized tracking. For those strategies using ITS, we developed methods to forecast bus arrival times to a stop and the number passengers on board the bus.

In terms of minimizing the average passenger trip time the ITS strategies outperformed the non-ITS based strategies for the randomly generated problem sets, though not for the OCTA dataset. Strategy #7, which does not preset the maximum holding time and determines it from minimizing the total waiting time among passengers currently at the stops and those forecasted to arrive before the bus arrives, was the best performing ITS based strategy in terms of minimizing the average passenger trip time. This strategy tends to balance the time saving for transfer passengers because of holding and delay for on-board or originating passengers at subsequent stops. This strategy provides the biggest advantage when the expected actual travel time is close to the scheduled travel time, when the headway is large, and with a large number of connecting buses.

Overall, it is disappointing that ITS did not provide larger time savings in our analysis. **A** fundamental reason is that in many situations it is optimal to do either of the following: (1) leave immediately, whether or not connecting buses have arrived (no hold), or (2) wait as long as possible until all connecting buses have arrived. These extreme alternatives require no communication and no-ITS. ITS is more beneficial in intermediate cases, where a connecting bus incurs a small delay, and it is more advantageous to wait for its arrival that to depart without the connecting passengers. These benefits must be weighed against the considerable cost of installing and maintaining a tracking and communication system. Though a cost-benefit analysis was not performed for this work, timed transfers alone do not seem to justify the installation of ITS. The savings per passenger appear to be no more than 1 minute, which translates into annual time savings on the order of 500 to 2000 hours per bus. Savings of this magnitude may be sufficient to justify an ITS installation, with payback within a few years. More generally, the savings are highly site specific, and should be evaluated on a case by case basis, taking into account the factors described in this paper.

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APPENDIX A: DERIVATIONS

The following discussion mathematically summarizes the departure time under the different holding strategies when buses are not allowed to depart before the scheduled time. The early departure cases can be developed in a similar manner.

Control Strategy 1

$AD_i = \text{Max}(AA_i, SD_i)$

Control Strategy 2

$AD_i = \text{Max}(AA_1, \ldots AA_n, SD_i)$

Control Strategy 3

$AD_i = \text{Min}(\text{Max}(AA_1, \ldots, AA_n, ,SD_i), (SD_i + \text{Holding Time}))$

Control Strategy 4

$AD_i = \text{Max}(SD_i, \text{Max}(t:\ t < (SD_i + \text{Holding Time}) \text{ for } t = TNOW, FA_1, FA_2, \ldots, FA_n))$

Control Strategy 5

$$AD_i = \text{Max}(SD_i, \text{Max}(t:\ t < (SD_i + \text{Holding Time}) \text{ and } (\sum_{FA_j < t} TP_{ji} > \text{Threshold Value}) \text{ for } t = TNOW, FA_1, FA_2, \ldots, FA_n))$$

Control Strategy 6

$$AD_i = (t : \text{Min}(P_i (t - \text{Max}(SD_i, TNOW)) + \sum_{FA_j < t} (t - FA_j)\, TP_{ji} + \sum_{FA_j > t} (FA_{n(i)} - FA_j)\, TP_{ji} \text{ for } t = TNOW, FA_1, FA_2, \ldots, FA_n))$$

Control Strategy 7

$$AD_i = (t : \text{Min}(P_i (t - \text{Max}(SD_i, TNOW)) + \sum_{S} \sum_{FA_j < t} (t - FA_j)\, TP_{ji} + \sum_{S} \sum_{FA_j > t} (FA_{n(i)} - FA_j)\, TP_{ji} \text{ for } t = TNOW, FA_1, FA_2, \ldots, FA_n))$$

where:

i	Index of bus holding at the stop
j	Index of any approaching connecting bus to the stop for $j=1,\ldots,n$
S	Set of current and subsequent bus stops
$n(i)$	Index of the next bus arrival for line i

AD_i	Departure time for bus i
SD_i	Scheduled departure time for bus i
AA_i	Actual arrival time of bus i
FA_i	Forecast arrival time of bus i
TP_j,	Expected number of transferring passengers from bus j to bus i
P_i	Number currently on bus i
TNOW	Current time

APPENDIX B: INTERVIEW FORM

Center Information:

1. Name:____
2. Title:____
3. Position:____
4. Phone No:____
5. Agency:____
6. Location:____

Location Capability:
(Summary: To determine the technological capabilities of the TMC)

1. How many people run the day to day operations of the TMC?

2. What are the hours of operation for the center?
   A. Weekdays-
   B. Weekends-

2a. Does the center vary its workforce dependent upon the busiest times of the day?

3. What types of hardware are currently being used or are to be implemented by the facility? (product name/type)

3a. To follow up, what type of software packages are being used?
For example ______________________________

4. Does the facility have remote tracking capability like GPS, Loran C or Signpost Odometer to monitor the busses?

4a. What percent of the busses are equipped?

4b. What percent of the fleet is covered?

4c. How is the information generated by the tracking system used?

4d. Was this its intended purpose?

5. Is there a vehicle component monitoring system or data recorder being used?

6. What types of automated payment systems are in place if any? (product name/type)

Objectives of the Management center:
(Summary: Determine the reason for implementation)

1. What was the driving force behind setting up the TMC/Dispatch center?

2. With regards to purchasing the remote tracking devices, how would you rate the importance of the following on a scale of 1 to 5, 5 being most important and 1 being least important:

a. Customer Satisfaction	1	2	3	4	5
b. Productivity	1	2	**3**	4	5
c. Security	1	**2**	3	4	5
d. Funding Availability	1	2	**3**	4	5

3. With regards to purchasing vehicle component monitoring systems, how would you rate the importance of

a. Customer Satisfaction	1	2	**3**	4	5
b. Productivity	1	2	**3**	4	5
c. Security	1	2	**3**	4	5
d. Funding Availability	1	2	**3**	4	5

4. With regards to purchasing automated payment systems, how would you rate the importance of the following:

a. Customer Satisfaction	1	2	3	4	5
b. Productivity	1	2	**3**	4	5
c. Security	1	2	3	4	5
d. Funding Availability	1	2	3	4	**5**

5. Did a consultant plan the setup of the center and the related technologies? If so, what type of post implementation services do they provide?

Usefulness of Technology
(Summary: Find out how the center is being used)

1. What type of response action does the center take for a late bus?

1a. How often is this type of action taken by the center per week?

2. What type of response action does the center take for a disabled bus?

2a. How often is this type of action taken by the center per week?

3. Does the driver have direct communication with the transportation center and it's information?

3a. Does the driver have direct communication with maintenance or security?

4. Has the facility been used as it was originally intended?

4a. If not, then how is it being used differently?

Usefulness of TMC:
(Summary: Quantitatively evaluate the effectiveness of what was implemented)

1. On a scale of 1 to 5, 5 being best and 1 being worst, how has technology affected:

a. Reduction in on the road repairs/breakdowns	1	2	3	4	5
b. Bus maintenance	1	2	3	4	5
c. Effort to create bus schedules	1	2	3	4	5
d. Schedule efficiency	1	2	3	4	5
e. Amount of overtime/drivers wages	1	2	3	4	5
f. Fare collection	1	2	3	4	5
g. Dispatching	1	2	3	4	5

2. Was the center ever evaluated for effectiveness/productivity? If so, what were the results of these reports? (Can we get copies?)

3. What suggestions do you have that would improve the facility?

4. What is the biggest accomplishment of the center?

5. What was the biggest disappointment with the center?

APPENDIX C: SURVEY PARTICIPANTS

AC Transit Authority
Bart, Oakland
Golden Gate Transit, San Francisco
King County Transit Authority
Massachusetts Bay Transportation Authority, Boston
MATRA Atlanta
Metro Houston
Metro transit authority of Harris County, Houston
METRO, Minneapolis
Minnesota DOT
MTA, Los Angeles
Ride on Montgomery, MD
Sacramento Transit District
Sam Trans, San Mateo
San Diego Metro
Santa Barbara Transit
Santa Clara Valley TA
Santa Cruz Metro
SORTA, Cincinnati
Transit Authority of Northern Kentucky, Fort Wright
Tri Delta Transit Authority
VIA, San Antonio
Western County Contra Costa Transit

Table 3. Holding Strategies

Strategy		Information Used					Holding Criteria			Implementation		
		Schedule	Connecting Bus Arrived/Not Arrived	Forecasted Arrival Times	Number of Transferring Passengers	Number of Passengers at Subsequent Stops	Forecast Arrival Within Time Window	Transferring Passengers>Minimum	Net Reduction in Waiting Time	Maximum Holding Time	Hold Indefinitely	No Hold
1	No Hold											X
2	All Hold		X								X	
3	Maximum Scheduled	X	X							X		
4	Forecast Time			X			X			X		
5	Forecast Time/Pass			X	X		X	X		X		
6	Net Wait at Stop			X	X		X	X	X	X		
7	Net System Wait			X	X	X	X	X	X	X		

Table 4. Forecasted ArrivalIDeparture Time when ST=2.5, σ = 1.5, γ = 0.2

Difference Between Forecasted and Acutal Arrival Time

	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Stop 7	Stop 8	Stop 9	Stop 10
stop 1	0.151303	0.24987	0.11108	0.11718	0.0645	0.0319	0.1309	0.2562	0.2972
stop 2	0	0.3063	0.10183	0.10653	0.0559	0.0257	0.127	0.2551	0.2956
stop 3	0	0	0.08007	0.05764	0.0592	0.0521	0.0737	0.2244	0.2876
stop 4	0	0	0	0.04981	0.1006	0.0796	0.0548	0.2086	0.2743
stop 5	0	0	0	0	0.0792	0.0921	0.0453	0.2016	0.2696
Stop 6	0	0	0	0	0	0.0626	0.0355	0.1929	0.2634
stop 7	0	0	0	0	0	0	0.0433	0.1782	0.256
Stop 8	0	0	0	0	0	0	0	0.1538	0.221
stop 9	0	0	0	0	0	0	0	0	0.0291

Difference Between Forecasted and Actual Arrival Time

	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Stop 7	Stop 8	Stop 9	Stop 10
stop 1	0.05643	0.19115	0.16699	0.1437	0.0945	0.0876	0.1024	0.2681	0.3148
stop 2	0	0.1819	0.15634	0.1351	0.0883	0.0837	0.1013	0.2665	0.3138
stop 3	0	0	0.00783	0.02	0.0105	0.0304	0.0706	0.2585	0.3116
stop 4	0	0	0	0.0214	0.017	0.0115	0.0548	0.2452	0.3087
stop 5	0	0	0	0	0.0295	0.002	0.0478	0.2405	0.3052
Stop 6	0	0	0	0	0	0.0078	0.0391	0.2343	0.2993
stop 7	0	0	0	0	0	0	0.0244	0.2269	0.2914
Stop 8	0	0	0	0	0	0	0	0.1919	0.2764
stop 9	0	0	0	0	0	0	0	0	0.0925

Table 5. Forecasted Arrival/Departure Time when ST=2.5, σ = 1.5, γ = 1.0

Difference Between Forecasted and Acutal Arrival Time

	Stop2	Stop 3	Stop4	Stop 5	Stop6	Stop 7	Stop8	Stop 9	Stop 10
stop 1	0.10059	0.36978	0.29474	0.4112	0.5119	0.6126	0.877	1.0993	1.2184
stop 2	0	0.43518	0.38776	0.4433	0.5308	0.6173	0.8691	1.0832	1.2002
stop 3	0	0	0.11596	0.0281	0.0983	0.1873	0.4461	0.6795	0.7901
stop 4	0	0	0	0.0072	0.083	0.1457	0.3825	0.5885	0.6899
stop 5	0	0	0	0	0.0257	0.0365	0.228	0.3937	0.4833
Stop 6	0	0	0	0	0	0.0747	0.1062	0.2665	0.334
stop 7	0	0	0	0	0	0	0.1522	0.2893	0.355
Stop 8	0	0	0	0	0	0	0	0.0971	0.1624
stop 9	0	0	0	0	0	0	0	0	0.0039

Difference Between Forecasted and Actual Departure Time

	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Stop 7	Stop **8**	Stop **9**	Stop 10
stop 1	0.0654	0.4107	0.40401	0.5376	0.6873	0.7248	1.0022	1.2223	1.3569
stop 2	0	0.50372	0.43607	0.5565	0.692	0.7169	0.9861	1.2041	1.333
stop 3	0	0	0.02093	0.124	0.262	0.2939	0.5824	0.794	0.924
stop 4	0	0	0	0.1087	0.2204	0.2303	0.4914	0.6938	0.8174
stop 5	0	0	0	0	0.1112	0.0758	0.2966	0.4872	0.6027
Stop 6	0	0	0	0	0	0.046	0.1694	0.3379	0.4364
stop 7	0	0	0	0	0	0	0.1922	0.3589	0.4387
Stop 8	0	0	0	0	0	0	0	0.1663	0.2373
Stop 9	0	0	0	0	0	0	0	0	0.0362

Table 6. Forecasted Arrival/Departure Time when ST=2.5, σ = 1.5, γ = 2.0

Difference Between Forecasted and Acutal Arrival Time

	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Stop 7	Stop 8	Stop 9	Stop 10
stop 1	0.07216	0.1934	0.3207	0.312	0.3272	0.4028	0.2444	0.1548	0.1782
stop ***2***	0	0.41352	0.4389	0.4224	0.4068	0.3312	0.4896	0.5792	0.5558
stop 3	0	0	0.1273	0.0456	0.0732	0.149	0.0094	0.099	0.0756
stop 4	0	0	0	0.0087	0.0068	0.0824	0.076	0.1656	0.1422
stop 5	0	0	0	0	0.0152	0.0908	0.0676	0.1572	0.1338
Stop 6	0	0	0	0	0	0.0756	0.0828	0.1724	0.149
stop 7	0	0	0	0	0	0	0.1584	0.248	0.2246
Stop 8	0	0	0	0	0	0	0	0.0896	0.0662
stop 9	0	0	0	0	0	0	0	0	0.0234

Difference Between Forecasted and Actual Departure Time

	Stop 2	Stop 3	Stop 4	Stop **5**	Stop 6	Stop 7	Stop 8	Stop 9	Stop 10
stop 1	0.60688	0.1934	0.3207	0.312	0.3272	0.4028	0.2444	0.1548	0.1782
stop 2	0	0.56623	0.4137	0.422	0.4068	0.3312	0.4896	0.5792	0.5558
stop 3	0	0	0.0543	0.058	0.0734	0.149	0.0094	0.099	0.0756
stop 4	0	0	0	0.0084	0.0068	0.0824	0.076	0.1656	0.1422
stop 5	0	0	0	0	0.0152	0.0908	0.0676	0.1572	0.1338
Stop 6	0	0	0	0	0	0.0756	0.0828	0.1724	0.149
stop 7	0	0	0	0	0	0	0.1584	0.248	0.2246
Stop 8	0	0	0	0	0	0	0	0.0896	0.0662
stop 9	0	0	0	0	0	0	0	0	0.0234

Table 7. Orange County Simulated Bus Lines

Simulated Line Number	Actual Number and Name
1	20(La habra-Brea)
2	25(Huntington Beach-Fullerton)
3	26(Fullerton - Yorba Linda)
4	29(Huntington Beach-Brea)
5	30(Cerritos - Orange)
6	39(Anaheim - Irivine)
7	41(La habra-Brea)
8	42(Seal Beach - Orange)
9	43(Fullerton - Newport Beach)
10	45(Costa Mesa - Orange)
11	47(Fullerton-Santa)*
12	49 (Brea-Santa)*
13	50(Orange-Long Beach)
14	53(Orange-Balboa)
15	54(Garden Grove - Orange)
16	55(Orange-Costa Mesa)
17	56(Buena Park - Santa Anamon)
18	57(Newport Beach - Santa Ana)
19	59(Costa Mesa - Anaheim)
20	60(Santa Ana - Westminster)
21	64(Santa Ana - Westminster Mall)
22	65(Balboa - Santa Ana)
23	67(Brea - Tustin)
24	69(Santa Ana - Orange/Fullerton)
25	70(Santa Ana - Sunset Beach)
26	72(Sunset Beach - Santa Ana)
27	75(Santa Ana - Laguna Hills)
28	85(San Clemente - Santa Ana)
29	89(Newport Beach - Laguna Hills)
30	91(San Clemente - Laguna Hills)
31	93(Rancho San Margarita-Laguna Hills)
32	99(Dana Point - Laguna Hills)
33	463(Santa Ana - Irvine)
34	177(Laguna Hills - Foothill Ranch)
35	203(Fullerton - San Juan Capisrano)
36	205(Anaheim-Laguna Hill)*
37	306(San Juan Capistrano-Irvine)
38	316(Costa Mesa-San Juan Capistrano)
39	333(Brea - Orange)
40	373(Fullerton-Placentia)
41	377(Laguna Hill- Dana Point)
42	388(Laguna Hill- Irvine)
43	424(Fullerton Trans Center-Raytheon)
44	454(Orange -The City)
45	462(Santa Ana Civic Center)
46	479(Santa Ana - Costa Mesa)
47	721(Fullerton - Los Angeles)
48	757(Dimand Bar-Santa Ana)

Table 8. Orange County Stop Numbers

Stop Number	Location
1	Fullerton Transportation Center
2	Lemon & Organethorpe
3	Anaheim & Lincoin
4	Haster & Katella
5	The City Area
6	17th & Bristol
7	Santa Ana Transit Terminal
8	Brea Mall Area
9	Brea&Bastanchury
10	State College & Nutwood
11	State College & Orangethorpe
12	State College & Lincoln
13	State College & Katella
14	Manchester Harbor
15	Santa Ana Main Place
16	6th & Flower
17	Laguna Hills Transportation
18	Imperial & Idaho
19	Brea Mall Area
20	Golden West Transportation Center
21	State College & Nutwood
22	Fullerton Parek 'N Ride
23	Continuing Education Center
24	Beach & Garfield
25	Brea Mall Area
26	Los Cerritos Center
27	Mall of Orange
28	Manchester Harbor
29	John Wayne Airport
30	Beach & Habra
31	State College & Nutwood
32	Coaset Highway & Balboa
33	Mall of Orange
34	Fullerton Transportation Center
35	Balboa & 23rd
36	16th & Irvine
37	The City Area
38	Mall of Orange
39	7th & Channel
40	Mall of Orange
41	Ocean Front & Palm
42	Chapman&Valley View
43	Santiago Canyon College
44	Orange Transportation Center
45	Anton Avenue of the Arts
46	Cypress College
47	Santa Ana Transit Terminal
48	Newport Transportation Center
49	Santa Ana Transit Terminal
50	Anton Avenue of the Arts
51	Kraemer & La Palma
52	Newport Transportation Center
53	Santa Ana Transit Terminal
54	Santa Ana Transit Terminal

55	Boeing
56	Ocean Front & Palm
57	6th & Flower
58	Brea Mall Area
59	Tustin Marketplace
60	Santa Ana Transit Terminal
61	State College & Nutwood
62	Santa Ana Transit Terminal
63	Warner & PCH
64	Warner & PCH
65	Santa Ana Transit Terminal
66	6th & Flower
67	Laguna Hills Transportation
68	Kmart Plaza
69	Laguna Hills Transportation
70	Newport Transportation Center
71	Laguna Hills Transportation
72	El Camino Real & Margarita
73	Laguna Hills Transportation
74	Banderas & Comercio
75	Laguna Hills Transportation
76	Doheny Park & Domingo
77	Laguna Hills Transportation
78	Santa Ana Transit Terminal
79	Michelson & Riparian View
80	Laguna Hills Transportation
81	Alton & Town Center
82	Hunt Wesson Foods
83	San Juan Capistrano Park-and-Ride
84	Junipero Serra &Rancho Viejo
85	John Wayne Airport
86	Hyland & Scenic
87	Junipero Serra &Rancho Viejo
88	Kraemer & Orbiter
89	Main Place
90	Park Place
91	State College & Lambert
92	Laguna Hills Transportation
93	Doheny Park & Domingo
94	Laguna Hills Transportation
95	Laguna Hills Transportation
96	Fullerton Transportation Center
97	Raytheon
98	Orange Transportation Center
99	City Drive &Garden Grove Blvd
100	Santa Ana Regional Trans Center
101	Santa Ana Regional Trans Center
102	Santa Ana Regional Trans Center
103	Harbor & MacArthur
104	Fullerton Park 'N Ride
105	Beaudry & 5th
106	Dimand Bar PNR
107	Santa Ana Transit Terminal

Table 9. Orange County Transfer Stops

Stop Numbe	Stop Location	Connecting Bus Lines
1	Fullerton Transportation Center	26,41,43,47,333,373,424
2	Lemon & Organethorpe	30,47
3	Anaheim & Lincoin	42,47,333
4	Haster & Katella	47,50,205,333
5	The City Area	45.47,49,54,56,333,454,479
6	17th & Bristol	47,4939
7	Santa Ana Transit Terminal	47,49,55,56,57,59,60,61,65,69,70,72,75,85,205,462 463,721,757
8	Brea Mall Area	20,29,41,49,85,333,373,757
9	Brea&Bastanchury	149,333
10	State College & Nutwood	125.26.41,49,69
11	State College & Orangethorpe	30,49
12	State College & Lincoln	42,49
13	State College & Katella	49,50
14	Manchester Harbor	39,43,50,205
15	Santa Ana Main Place	53,55,56,205,333,462
16	6th & Flower	55,59,60,65,75,85,205,462,721,757
17	Laguna Hills Transportation	75,85,89,91,93,99,177,203,205,306,316,377,388

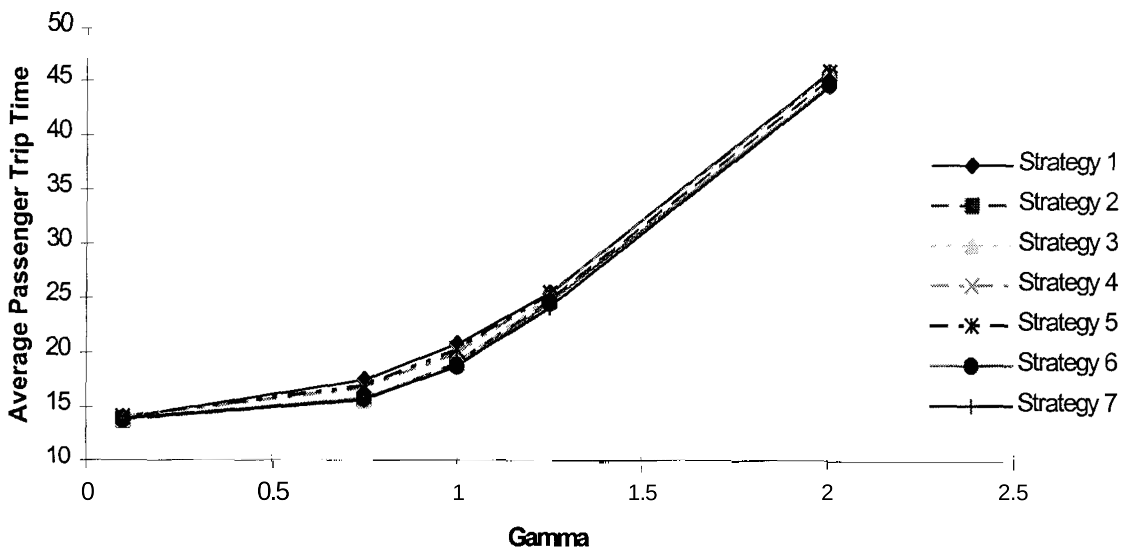

Figure 1. Average Passenger Trip Time (minutes) as a Function of γ

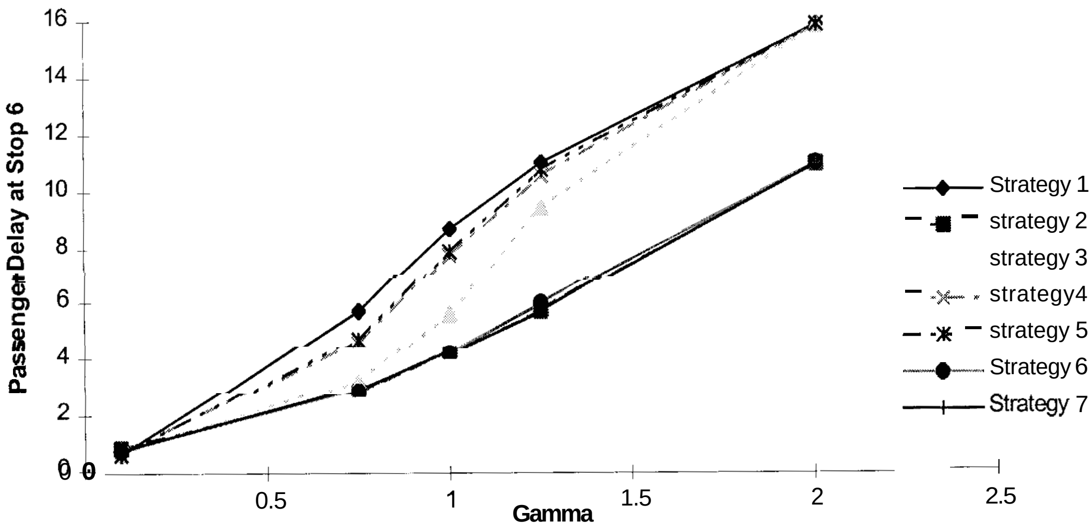

Figure 2. Passenger Delay (minutes) at Stop 6 as a Function of γ

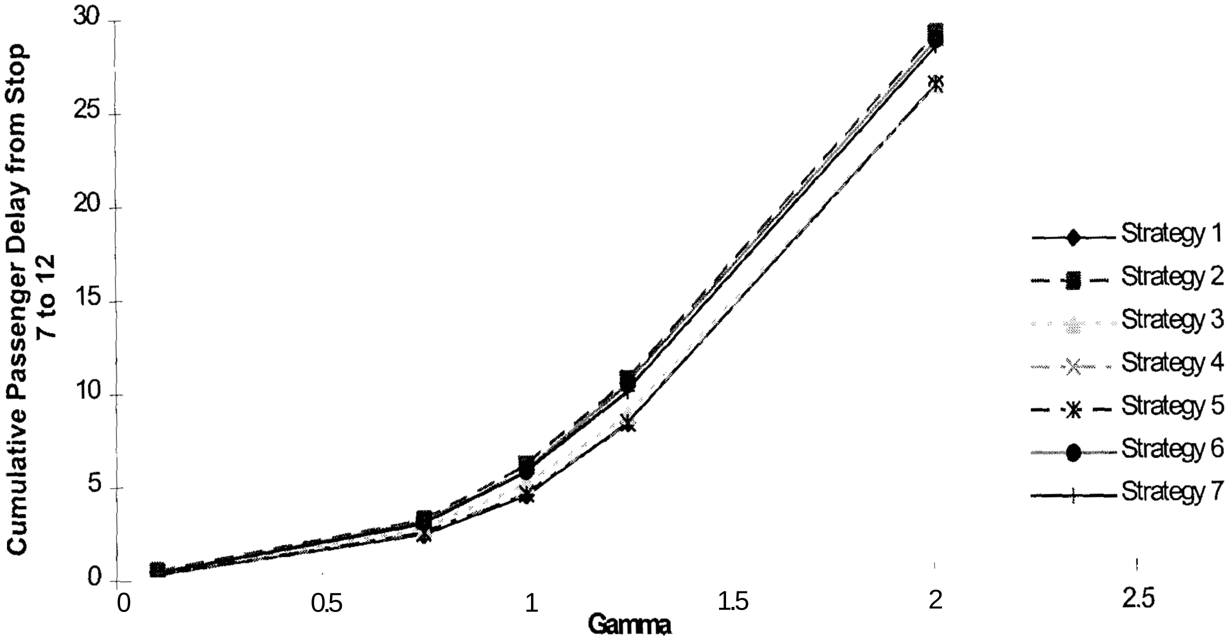

Figure 3. Total Passenger Delay after Stop 6 (minutes) as a Function of γ

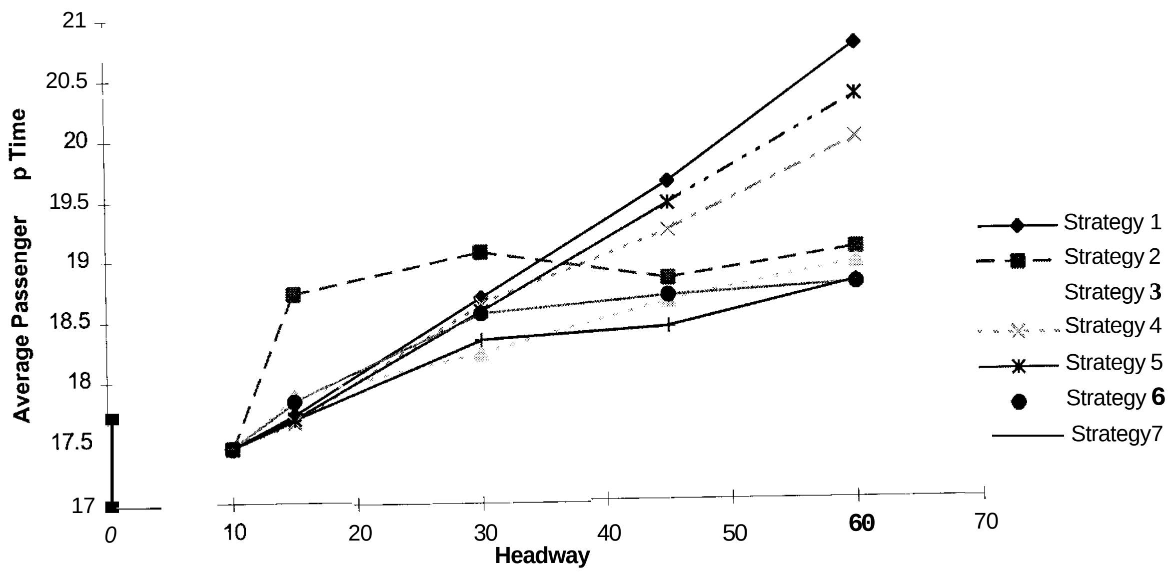

Figure 4. Average Passenger Trip Time (minutes) as a Function of the Headway

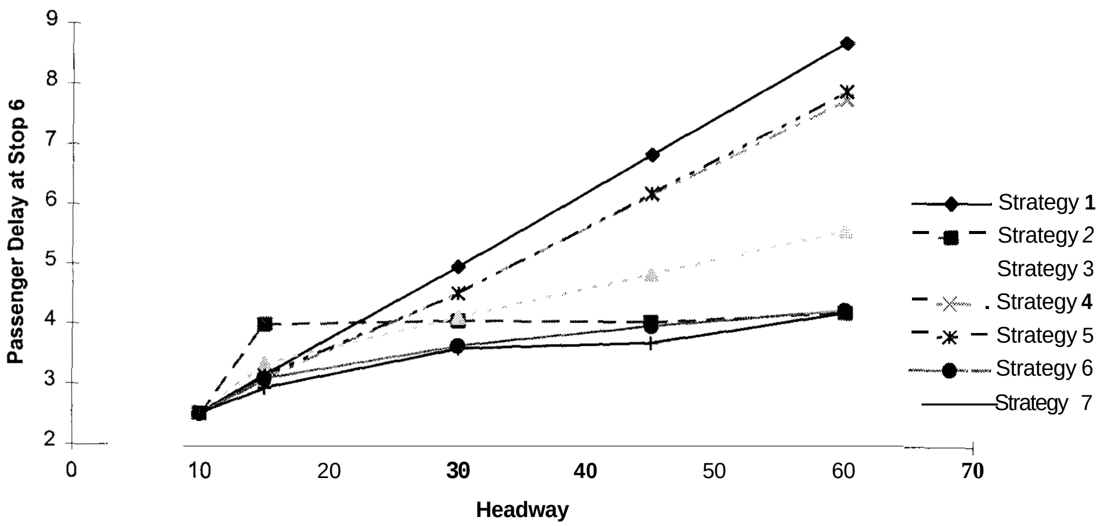

Figure 5. Passenger Delay (minutes) at Stop 6 as a Function of the Headway

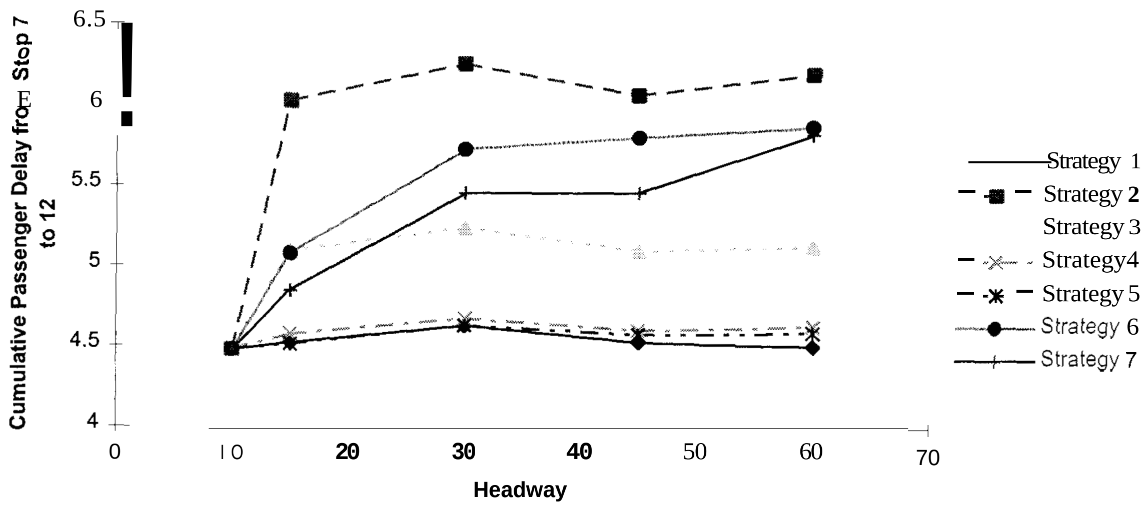

Figure 6. Total Passenger Delay (minutes) After Stop 6 as a Function of the Headway

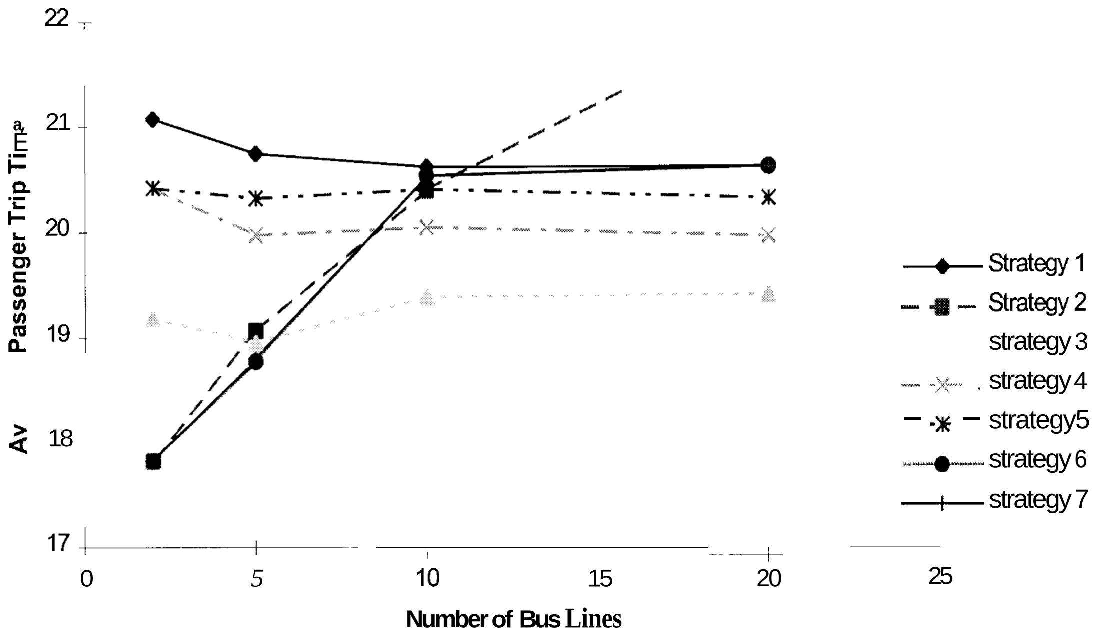

Figure 7. Average Passenger Trip Time (minutes) as a Function of N

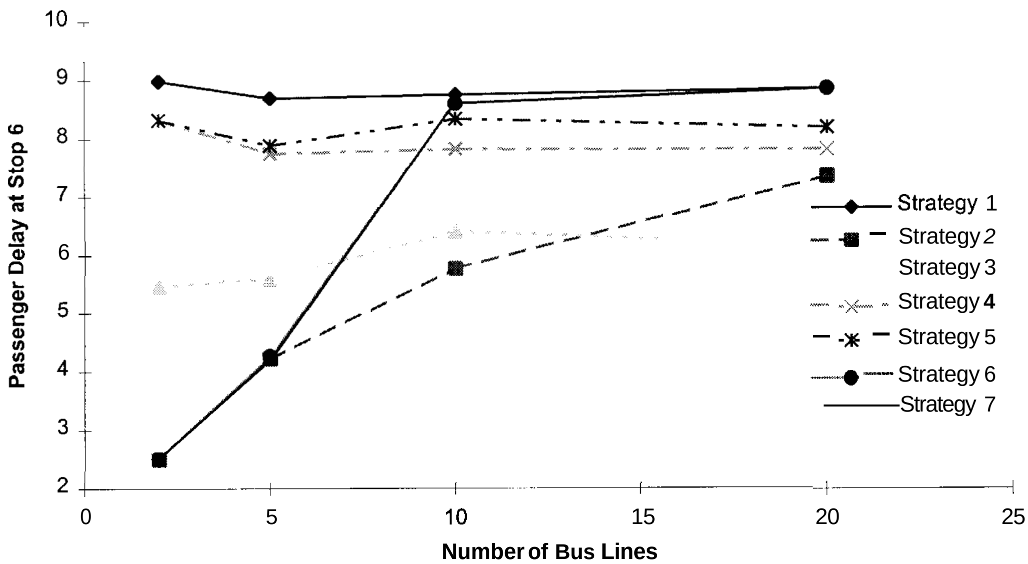

Figure 8. Passenger Delay (minutes) at Stop 6 as a Function of N

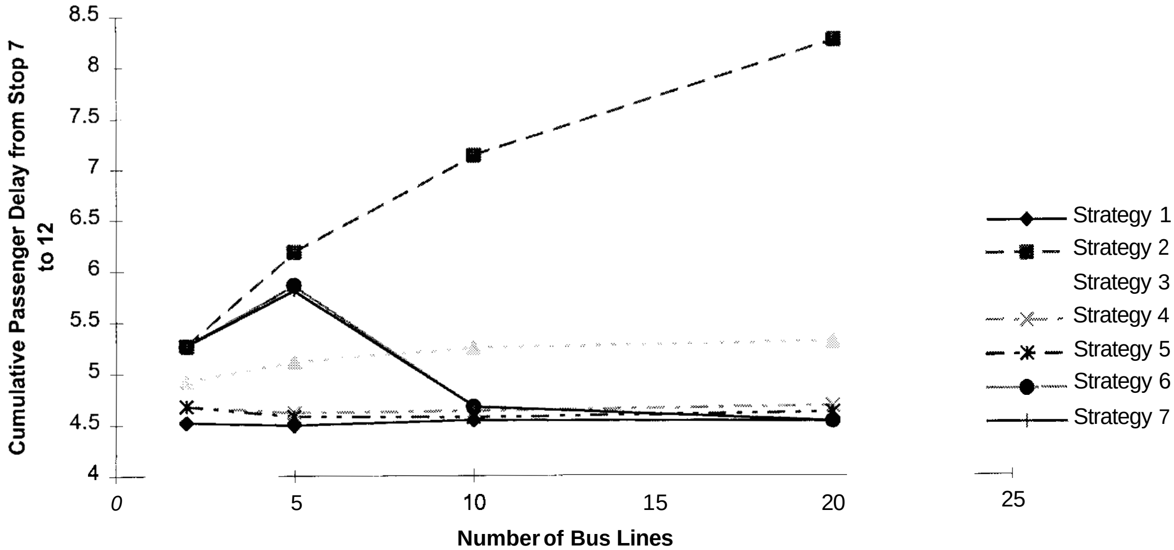

Figure 9. Total Passenger Delay (minutes) After Stop 6 as a Function of N