Reliability of Fare-Collection Systems for Rail Transit: An Overview

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The present performance of graduated-fare automatic collection equipment is compared with that of similar fare-collection systems, desirable performance is estimated, and research and development needs are identified. A series of flowcharts for three actual rail systems that indicated the range of functions and approaches that could be incorporated into a fare-collection system were developed. Queuing models could not be used directly to estimate the impact of the collection system on passenger flow without developing a two-stage model by use of the binomial probability distribution. Reliability data were collected by using interviews and the review of operating records. The data-collection methods varied greatly. Mean transactions between failures was found to be a useful and practical measure for comparing equipment reliability. The operating costs of rail transit fare-collection systems vary between 7 and 31 percent of revenues collected. The reliability of fare-collection equipment varies between 40 000 transactions/failure for a token-accepting turnstile to several hundred transactions per failure for a stored-value farecard vendor. Improved performance is obtainable, but the potential extent is unclear. Systems with a combined reliability of 0.22 percent failures/passenger can function without station attendants. It is important to specify failures in terms of component replacement and in terms of clearing of jammed tickets or money. The results provide an initial basis for comparing the performance of alternate fare-collection systems and focusing development resources.

This paper discusses various rail transit fare-collection systems (ranging from the simple to the complex), the performance of automatic-fare-collection (AFC) systems, methods of procurement, analysis of impacts on passenger flows, and longer-term fare-collection development needs for the industry. Interest in the reliability of AFC systems has increased as a result of the experiences of several new rail transit systems. This paper reviews this and related issues and reports on some of the systems analysis work conducted by the Jet Propulsion Laboratory for the Subsystem Technology Application to Rail Systems (STARS) program of the Urban Mass Transportation Administration (UMTA).

DESCRIPTIONS OF TYPICAL SYSTEMS

Fare-Collection Market

Almost $3 billion in passenger fares are collected annually in the United States. The largest proportion is for bus transit. Since the bus driver is available to supervise the operation of the fare box, most bus-fare functions can be completed with a minimum of complexity. Commuter rail collects almost $400 million annually in passenger revenue. In urban rail transit, which collects $700 million annually in revenue, high passenger volumes in limited space and time have necessitated the use of passenger-fare-processing machinery (1, p. 15).

System Elements

Urban transit fare-collection systems contain two essential elements: a method of collecting the revenue from the passenger and a method of controlling access to the station or the train. There are other elements, but some form of these two will be found in any system. At a more detailed level, additional elements can be identified. These include form of payment, fare structure, ticket type, ticket vending, change making, entry-exit gates, money processing, compliance enforcement, equipment maintenance, station attendant, passenger assistance, and management information.

Many of the definitions of system elements will be obvious from a discussion of these elements later in this paper. However, there are so many variations to fare structure that it is worthwhile to define this element more precisely. This is done in Table 1, which is adapted from a recently completed survey of fare-collection equipment (2, p. 5).

The term automatic fare collection relates to the extent of manual effort required to interface with passengers and operate a system that implements a particular fare structure. Common usage usually associates AFC with a variable-fare structure, although it could also apply to a fixed-fare system, depending on the specific equipment used.

For many of these elements, there may be as many as 10 different methods of performing a function. The number of potential combinations, and thus of different fare-collection systems, is enormous. A good understanding of the interaction of these elements can be readily obtained by examining several different systems now in use.

System Flow Charts

Three systems that illustrate a variety of fare-collection techniques were selected and are shown in Figures 1-3. These charts describe several of the essential differences between the systems; they are not a complete description. The systems are examined here in order of ascending complexity.

New York City Transit Authority

The form of fare payment on the New York City Transit Authority (NYCTA) is cash, paid to the station agent in exchange for a token. The fare structure is flat--that is, the same between any two stations of the system. This can lead to great inequities in charges per mile for different passengers. Nevertheless, most urban transit systems operating within one political subdivision (with distances of less than 1.1 miles between stations) have selected a flat-fare structure (3).

A token is used as a ticket to gain entry. These tokens are manufactured especially for the NYCTA, which sends inspectors into the contractor's plant to prevent unauthorized production. The token is used thousands of times in its life, and the cost per use is negligible.

As the flow chart in Figure 1 indicates, 50 percent of the passengers will already have a token and proceed directly to the gates. One-third of the passengers will purchase from one to several tokens from the station agent, who performs the ticket-vending and change-making functions. More than 8 percent of weekly riders will request a return coupon valid for a free ride by senior citizens, the handicapped, and, on weekends, all passengers.

The prime entry-exit gate is a mechanical turnstile that accepts the token. The turnstile turns are recorded on a meter enclosed in a sealed welded steel box. The station agent collects tokens from the turnstile several times a day and sells

them to the public. The agent is financially responsible for any failure of the token sales and cash collected to balance against turnstile registrations. The revenue section collects funds from the station agent. As the agent counts tokens, he or she visually inspects them for counterfeits (slugs).

More than 15 percent of NYCTA passengers enter without using a token. These include the return portion of senior citizen and weekend half-fare trips plus students who have passes purchased through their schools. These passengers enter through a slam gate supervised by the agent.

The equipment is reliable and rarely needs maintenance. In addition to providing information, the presence of a station attendant gives an added sense of security to passengers. Even if all station-agent functions were replaced by reliable equipment, management might still decide to keep agents in the station.

Port Authority Transit Corporation

The Port Authority Transit Corporation (PATCO) uses a zone-fare structure (see Figure 2). The system length is 22.5 route-km (14 route miles), broken into five zones; fares range between $0.55 and $1.15 and average $0.12/zone. A thin [0.025-mm (0.0011-in)], magnetically encoded, stored-ride plastic ticket is used. Tickets cost $0.12 new but are used hundreds of times. The cost of reencoding and reissuing a used ticket is $0.01. Printing over the plastic is not done.

Forty percent of riders purchase their tickets in the form of 10-ride tickets from newsstands. Newsstands in the PATCO stations are required to sell tickets and are allowed 30 days to pay for them. This cash float is a strong incentive. Single-ride and two-ride tickets are sold through cigarette-type vending machines, in which they are stored in separate stacks according to the particular zone-to-zone combination.

Thirty-five percent of PATCO passengers use separate change makers before using the vending machines. The change makers are rented from and maintained by the manufacturer.

The entry gate has a card transport that moves the ticket through the machine. When the ticket is inserted, its validity is checked for proper entry zone, and a code is written that indicates that the next transaction must be an exit transaction. One ride is also deducted. At the exit station, the gate checks the ticket for the proper zone. A ticket with remaining rides will be returned to the passenger; otherwise, it will be captured. Used tickets are collected, sorted, reencoded, and resold.

Money processing is greatly simplified because of the bulk sales to newspaper stands. The revenue department staff collects funds from the vendors and change makers and restocks them.

Compliance is aided by closed-circuit television and police patrols. Equipment maintenance and jam rates are low enough to allow unattended stations. Before each rush hour, roving supervisors check each machine to ensure that it is working properly. In the busier stations, a supervisor is assigned throughout the rush hour.

At other times, a patron may use the phone for assistance. If his or her ticket is not valid at that station, the additional fare is deposited

Table 1. Fare structures in order of increasing complexity.

Type of Fare	Description
Predetermined	
Fixed (single rate)	No extra charge for transfers, same rate for all passengers on all routes between any two points
Flat (multirate)	One basic rate, may or may not charge for transfers, reduced rate for certain passenger categories, reduced rate for off-peak hours, Sundays, and holidays
Variable (computed)	
By zone	Fare rates in increments according to number of zones traversed by passenger, can provide fare classes as a function of day and passenger category
By distance (graduated)	Fare determined for each journey by distance traveled, reduced-fare classes can be provided by passenger category and time period

Figure 1. New York City Transit Authority flowchart: manned flat fare.

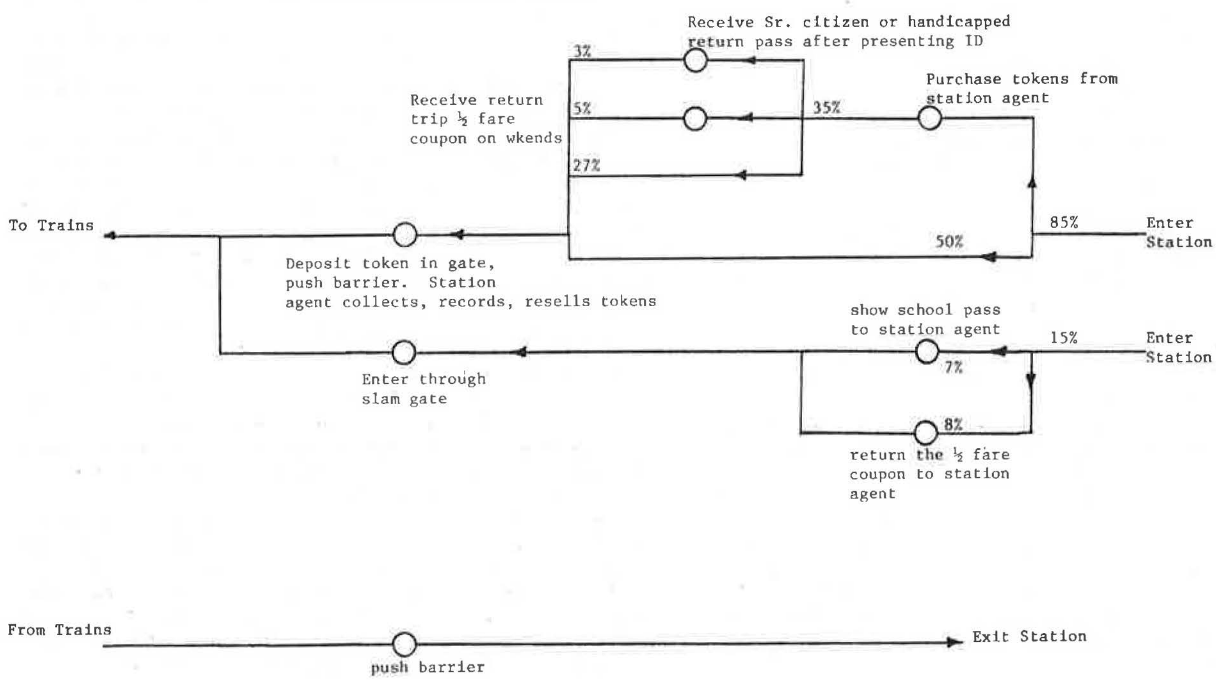
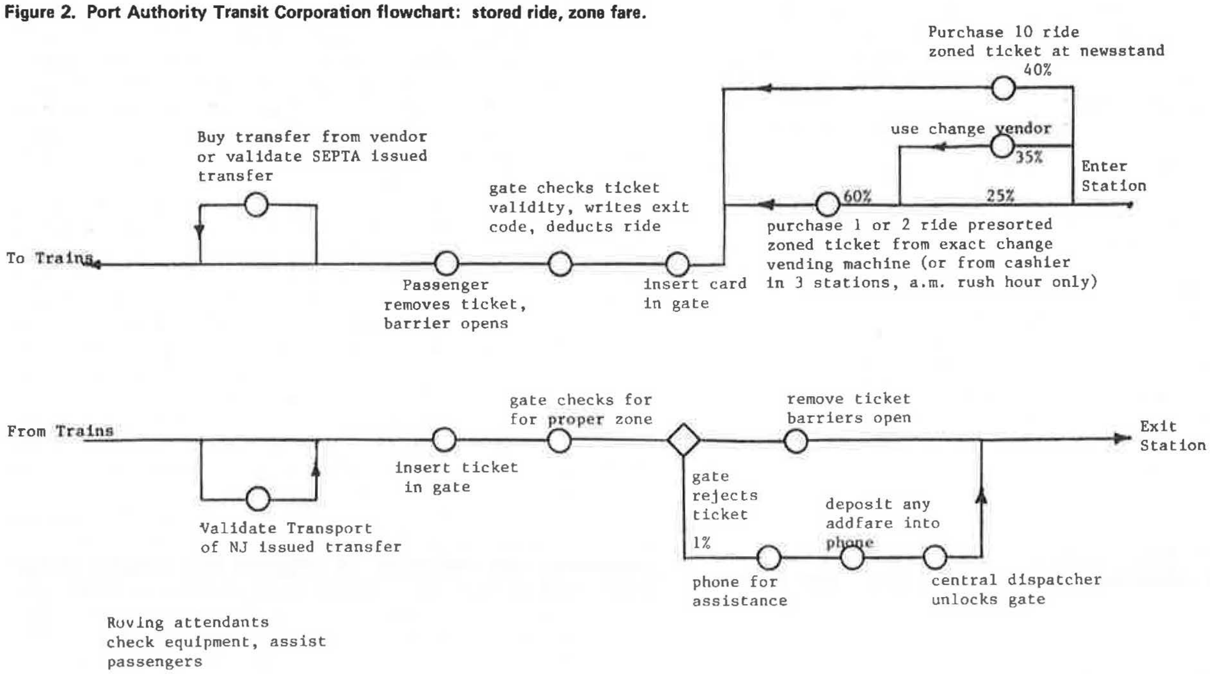


Figure 2. Port Authority Transit Corporation flowchart: stored ride, zone fare.



directly into the phone and a gate is unlocked by the observer of the television monitor.

Washington Metropolitan Area Transit Authority

The last and most complex of the three illustrative fare-collection systems is that of the Washington Metropolitan Area Transit Authority (WMATA). The Metro system is similar to the Bay Area Rapid Transit (BART) System in that it serves several political entities and is a combination commuter railroad and urban transit system. These conditions encouraged the adoption of a distance-related fare structure, which charges longer trips more than shorter ones and facilitates the accounting of subsidies from the various local governments that support the system.

It is also a stored-value instead of a stored-ride system--a marketing incentive. It has been stated that, if commuters have a valid subway pass in their pockets, they are more likely to use the subway for occasional short, noncommuting trips than if they had to pay a separate entry fee.

The fare structure is very precise. It charges 40 cents for entry, which allows 5 free km (3 miles) of travel. A fee proportional to the average of the air-line and route distance (11-12 cents/km) is charged for additional travel on each trip. The charge is rounded off to the nearest 5 cents. The system also accommodates special discount-fare programs for students, the elderly, and the handicapped, as well as midday discounts.

A very thin, magnetically encoded paper fare card is used to gain entry. The cost of each card is about 1 cent. The remaining value of the card can be printed onto it over its protective coating. The card is usually used fewer than 10 times before it begins to wear. Because the coding system is not particularly complex, it is possible that a limited number of persons have broken the code and regularly upgrade low-value farecards to an unauthorized higher value. In addition, it is possible for vendors to erroneously issue overvalued cards. It is very difficult to detect and locate any pattern of fare evasion, since there is no physical evidence. One detection method is to have the exit gate capture all cards and reissue new ones. The captured cards would be examined for fraudulent ones.

Fare-collection fraud can be attributable to either passengers or staff. All systems experience some fraud, but published data are not readily available. A key principle of fraud control is that its cost should be less than the amount of money saved. European experience with self-canceling surface transport fare-collection systems indicates that most systems lose between 0.5 and 5 percent of their revenue because of fraud (4). The systemwide imbalance between the value extracted from AFC tickets and the value of tickets sold at vendors is a measure of fare evasion in graduated-fare systems. Fare evasion for graduated- and flat-fare systems in the United States is in the same 0.5-5 percent range.

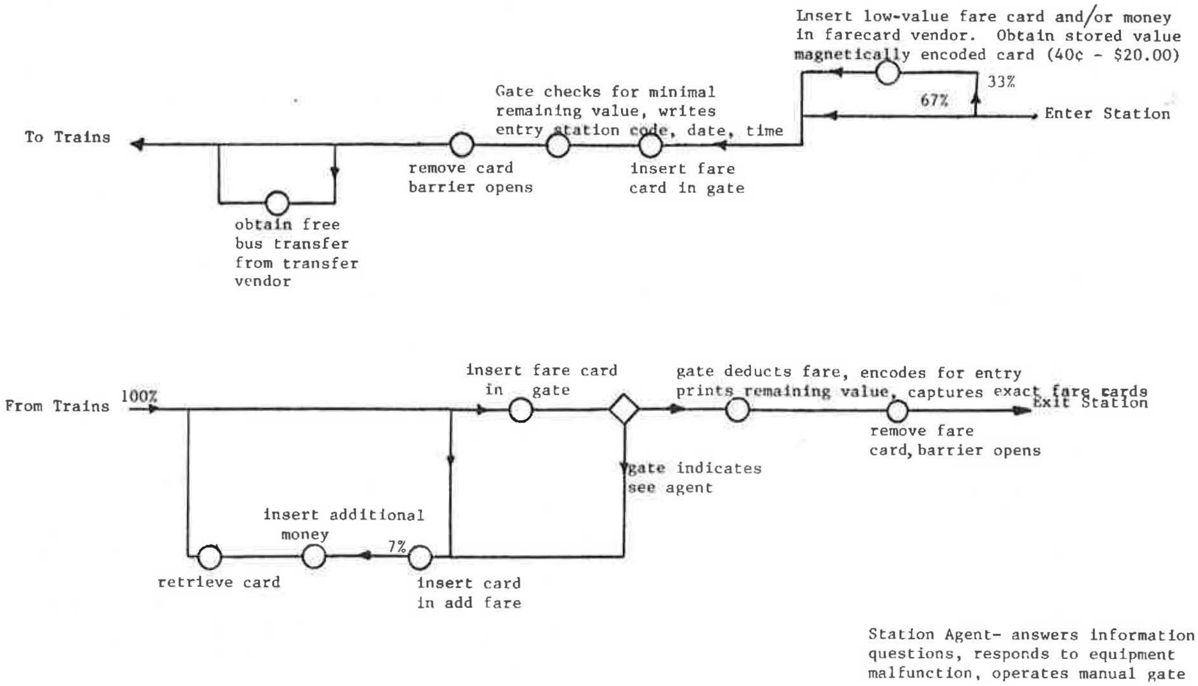
Farecards are sold by a versatile vending machine that accepts $1 and $5 bills, change, and low-valued farecards; issues a new farecard with any value between $0.40 and $20; and returns change.

The form of payment is cash, which has led to unexpected problems. Dollar bills, which cost about 1 cent to produce, are designed to be kept in circulation for 9 months, but it has been estimated that they currently remain in circulation for 18 months. Coins can usually last 17 years. The lowered physical quality of money leads to more jams in vendor and "addfare" machines. A common problem is bent dimes that have been used by passengers as emergency screwdrivers.

Thirty-three percent of persons entering a station will use the farecard vendor, and 67 percent will proceed directly to the gates (see Figure 3). A September 1978 WMATA survey indicates that approximately one-third of farecard vendor users are trading in lower-value cards.

The farecard is inserted in the gate and checked for minimal remaining value, and an entry and location code is magnetically written on the ticket. The card moves through the gate via the transport to the exit slot, where it is removed by the passenger. Card movement is intended to pace the movement of passengers through the gate.

Figure 3. Washington Metropolitan Area Transit Authority flowchart: stored value, distance-related fare.



While in the control zone of the station, a passenger may obtain a free rail-to-bus transfer from a separate transfer dispenser. A need for a machine-issued and readable bus-to-rail transfer has been expressed.

In exiting a station, the passenger inserts the farecard in the exit gate, where the travel distance is calculated and the proper fee deducted from the stored value. The remaining value is printed on the card. If the value is not sufficient, the card is rejected and a message to see the agent is displayed. The patron must then go to the agent, who will direct him or her to the addfare machine, a simplified vendor that upgrades the ticket upon insertion of the proper fee. The upgraded farecard is then used in the exit gate.

Money is collected from the vault chambers in the farecard vendors and addfare machines by revenue service and collection department staff. The station attendant does not have access to the vaults or perform any functions that involve the handling of money. This increases the attendant's security.

Compliance is enforced by closed-circuit television, the station agent, and the police.

The required equipment maintenance on the Washington, D.C., system has been much greater than desired. Clearance of jams and calling for maintenance repair are so frequent that the concept of reduced-level station manning is practically eliminated. Rapid response to maintenance calls by a large, widely distributed maintenance staff can lead to a high rate of equipment availability, in spite of frequent malfunctions, but at great expense.

Passenger assistance is provided by the station attendant.

The data acquisition and display system (DADS) monitors equipment performance and activity. This system also provides a sealed written record of each machine's transactions and receipts and generates a clock code that is used by the entry and exit gates to determine fares based on time of entry and to reject farecards where the time between entry and exit is greater than a prescribed value.

Cumulative statistics on fares extracted at gates, passenger flows, and vending-machine sales and receipts can be centrally polled at each mezzanine kiosk.

Reliability of System Elements

The reliability of the overall fare-collection system is determined by its individual components. Table 2 gives the mean number of transactions per maintenance action for several types of fare-collection equipment. It indicates vast differences in reliability and shows a trend toward decreasing reliability with increasing equipment complexity. It can be used as a guide in estimating achievable levels of improvement for present AFC equipment.

There are several definitions of reliability that can be used to relate equipment performance to activity. Performance can be described in terms of the capability to (a) complete all functions, (b) complete the more critical functions, (c) be repaired by level 1 (fingertip) maintenance, and (d) be repaired by level 2 maintenance (the replacement or adjustment of components). The mean number of transactions per maintenance action was selected as the definition that best corresponds to the ability of a fare-collection system to process large numbers of passengers with minimal expense and delay. It is also broad enough to apply to the various practices in use on different systems. (Maintenance actions include repair orders completed by maintenance staff, jams cleared by station attendants, and repairs completed by patrolling maintenance staff. The ratio of jams to hard failures usually varies between 3:1 and 5:1.)

The data were collected from different transit systems under varying conditions. In some cases, excellent records were available on maintenance actions and transaction rates. In other cases, an example of the best estimate available, without a special survey, was that one-third of the machines were serviced each day by roving teams of maintenance personnel in addition to logged calls.

The definition of failure also varies according

Table 2. Typical reliability of fare-collection equipment.

System	Type	Mean Transactions per Maintenance Action
NYCTA	Flat fare, token-accepting turnstile	40 000
CTA	Flat fare; coin-accepting, transfer-issuing turnstile gate	
	Type 1	800
	Type 2	2500
PATH	Flat fare, coin-accepting turnstile	11 000
	Flat fare, pass card, reader-conductive ink	≥50 000
PATCO	Entry-exit gate, magnetic card, stored ride, zone fare	6000
	Ticket vendor, sorted tickets	900
	Change maker	≥2000
BART	Graduated fare, magnetic-card-reading entry-exit gate that computes and prints remaining value	
	Type 3	4200
	Type 4	1200
	Farecard vendors	
	Type 3	1100
	Type 4	400
	Addfare type 3	1100
WMATA	Graduated fare, magnetic-card-reading gate	
	Entry gate	2000
	Exit gate (computes and prints)	500
	Farecard vendors	100
	Addfare	75
European surface transport	Cancelling machines	20 000
	Ticket-issuing machines	5000-10 000

Notes: CTA = Chicago Transit Authority; PATH = Port Authority Trans-Hudson.
Types refer to different manufacturers of similar equipment. WMATA data are for rush hours only.

to the system. On the NYCTA system, the station attendant performs no repair functions, and any equipment jam will result in a maintenance report. The BART station attendant will apply fingertip maintenance to clear farecard and money jams. These failures will never be reported, whereas a hard failure that requires a maintenance technician will be.

The NYCTA turnstile is simple, inexpensive, and extremely reliable (40 000 transactions/failure). The acceptance mechanism tests only the size of the token. It is estimated that 90 percent of the failures are actually jams caused by the insertion of foreign objects into the token slot. Records indicate that the jam rate will increase by 25 percent in the year after a fare increase. There is a 100 percent correlation between turnstile registrations and turns.

The CTA turnstile accepts coins and issues transfers. Some passengers will overpay for convenience, and the money received will not correspond to the barrier turns. Coins are collected in the type 2 machine in a sealed steel cylinder that is removed from the machine by the Revenue Department. The reported rate of transactions per failure for those machines appears to be unusually poor considering their lack of complexity. These data deserve closer investigation.

The PATH system uses turnstiles that are similar to CTA's except that they do not issue transfers. Their failure rate is 11 000 transactions/failure. Most of the failures are attributed to jams resulting from bent dimes. PATH has wired to several of its machines an independent change maker that accepts dollar bills, returns change after subtracting the fare, and releases the barrier lock.

A key observation is that the PATH system is capable of operating without station attendants and with equipment that has a rate of 11 000 transactions/failure. The system operates with a failure rate of 1 failure/11 000 passengers for turnstiles plus 1 failure/2000 passengers for the change makers. Assuming that one-quarter of the passengers use the change maker, the combined system failure rate is $1/11\ 000 + 1/4\ (1/2000) = 2.2 \times 10^{-4}$ failures/passenger. In other words, 0.22 percent of the passengers encounter a machine failure.

A similar performance criterion stated in previous studies should be noted (5, p. 47): "Observations made on other transit systems have indicated that any passenger confusion arising from the man-machine interface, which affects as many as 0.5 percent of the patrons, could easily be cause for general dissatisfaction." This would imply that, even if a machine were to "self clear" jams without the aid of a station attendant, at least 99.5 percent of passengers should be processed by the equipment without resort to manual assistance.

A year-long demonstration of nine Almex (Incentive AB of Sweden) multiride ticket cancelers was recently completed. This device is similar in appearance to a miniature time clock. The passenger inserts a multiride ticket into a slot, one ride is deducted by an internal paper cutter, and the passenger withdraws the ticket. The canceler makes contact with several electrically conductive stripes on the back of the ticket that form a binary on-off code.

PATH has placed the Almex cancelers on small stands in front of and wired to turnstiles. The gate can handle passengers who pay with cash or with tickets. The mean number of transactions per maintenance action was more than 50 000. Two passengers out of 1000 (0.2 percent) reported that they inserted their 10-ride ticket into the machine backwards and that, although the ticket was destroyed, the machine did not jam. Their crumpled ticket was exchanged for a new one by PATH.

The system was removed after the one-year test because of the cost of distributing tickets (commissions to retailers) and the lack of an urgent need for the added passenger convenience.

PATCO uses a zone-fare system with magnetically encoded plastic cards that are inserted into a card transport in the gate. No printing is done on the card, and few jams are caused by card wear. The mean rate of 6000 transactions/failure is twice that of BART or WMATA. The ticket vendor uses presorted stacks of different types of tickets. The rate of 900 transactions/failure is not as high as expected for such a simple machine.

The change makers used are separate units maintained and owned by the manufacturers and rented to PATCO. Their reported failure rate of 2000 transactions/failure appears to be better than when equipment with the same functions is incorporated as part of a larger, more complex machine.

The performance of BART and WMATA equipment is given in Table 2 for ease of comparison. No survey information was available from BART for the ratio of soft to hard failures. The ratio derived for WMATA was applied to BART and may lead to slightly pessimistic results.

The BART and WMATA equipment represents three different generations of the same basic design, two

at BART and one at WMATA. Normally, each generation of equipment under development would be expected to be many times more reliable than its predecessor. Such is not the case here. This may indicate a problem in the transferral of information or the procurement process. It also leads to a continued expectation that the performance of the basic design can be further improved.

Information concerning European surface transit was developed in a survey conducted by the International Union of Public Transport and reported in 1973 (4). The figure given in Table 2 excludes servicing that results from false alarms and vandalism. Equipment developed since 1973 or used in a station environment rather than on a bus or at a stop might perform better than indicated. The ticket-issuing machines described accept coins only, no bills.

Fare-Collection Operating Costs

Both the capital and operating costs of fare-collection systems vary tremendously. A gate can cost from $2000 to $30 000 depending on its complexity and its function. Additional costs are incurred in the structural design of stations, especially at mezzanines because of the space required for fare-collection equipment.

Operating costs of several fare-collection systems, derived from a survey conducted in 1977, are given in Table 3 (6). Because WMATA ridership and receipts have more than doubled since that time, the figures should be used cautiously. A more up-to-date survey of this information should be conducted.

Although it is not otherwise described in this paper, mention should be made of the honor system used in Hamburg. Passes are sold through banks, vending machines, and retail outlets. There is no entry or exit control, but inspectors ride the trains and check for valid passes. The operating cost of the system is 7 percent of the revenue collected, or 1.4 cents/ride.

In spite of its successful application in several European cities, the honor, or self-canceling, type of system probably has useful but less limited application in the United States. The demographics of American cities are different from those of Europe, where the wealthier and not the poorer people tend to live in cities (there are some signs that this may be changing). The level of criminal activity is often less, too. In many European cities, the police are not even armed.

UMTA is investigating the feasibility of a self-canceling fare-collection system for bus transit in the United States. If it proves successful and compliance and enforcement problems do not develop, this system, applied to rail transit, offers the potential for large reductions in the cost of fare collection.

SYSTEMS EVALUATION MODEL

Two-Stage Model

A model has been developed to relate the performance of individual pieces of equipment to transit-station characteristics. The model consists of two stages. At the first stage, the average availability of a certain type of machine (e.g., ticket vendors) is used to calculate the probability that a given number of similar machines in a bank of machines in parallel operation will be available for use. The second stage of the model is a queuing model for multiple servers, which yields probabilities of waiting time, average queue length, average time in the system, etc.

Use of a two-stage model greatly simplifies analytic description and also relates two of the major processes that occur during station operations. These are the out-of-service condition of one or several AFC machines and the subsequent increase in arrival rates and queues at the operating equipment. An effort was made to develop a one-stage, closed-form, analytic model, but this approach was discontinued.

Equipment Availability Model

The probability p that a given machine is available for service at any instance in time is called availability and is defined as

$$\text{Availability} = \text{MTBF}/(\text{MTBF} + \text{MTTR}) \qquad (1)$$

where MTBF is the mean time between failures and MTTR is the mean time to repair the equipment. By use of the appropriate service rate, availability can also be expressed in terms of mean transactions between failures.

Availability, therefore, takes into account the maintenance of the machine. Thus, if a failed machine is quickly put back into service through improved maintenance procedures or assignments, a higher availability results.

The probability that a specific number of machines in a bank of machines will be available for use at a given moment can be calculated by using the binomial distribution. Thus, if p is the probability that a machine is available for use (its availability), the probability that x machines out of a bank of n machines will be available is

Table 3. Estimated annual fare-collection operating costs for six systems: FY 1978.

Item	NYCTA	BART	Hamburg	PATCO	PATH	WMATA
Cost ($000 000s)						
Station personnel	80.8					
Stationary		3.8	0.3	0	0	1.6
Mobile		0.9	0.3	0.15	0.60	0.2
Equipment maintenance	3.5					
Field		0.6	0.03	0.16	0.16	0.8
Central		0.2	0.08	-	0.02	-
Collection	3.1	0.4	0.3	0.12	0.03	0.4
Revenue counting	2.2	0.3	0.04	0.03	-	0.3
Revenue accounting	0.3	0.1	0.2	0.01	0.22	0.06
Compliance enforcement	0.3	-	1.0	0.4[a]	-	0.02
Other	1.7	0.4	0.3	0.08	0.05	0.8
Total	91.9	6.7	2.6	0.95	1.1	4.2
Percentage of passenger revenue	19	31	7	7[b]	8.7	21

[a]With police.
[b]Without police.

$$[n!/x!(n-x)!]\, p^x\, (1-p)^{n-x} \tag{2}$$

Table 4 gives an example of probabilities for stations with nine fare gates where the individual gate availabilities (A) are either 0.85, 0.90, 0.95, or 0.975. These values are representative of field experience. For A = 0.95, the probability that eight of the nine gates are operable is 0.29; the probability that seven or fewer are operable is 0.057 + 0.006 + ... = 0.063. If the number of fare gates installed is based on 100 percent availability, this simple analysis indicates that, at least 6 percent of the time, at least two of the nine gates will be inoperable and large queues may develop.

The availability of the individual machine depends on equipment reliability (transactions per failure), passenger arrival rates, and the time required for a station attendent or maintenance technician to arrive at the scene and repair the equipment. Transactions per failure may also depend on the service rate. Several experts contend that, when AFC equipment is used at very high service rates, the solenoids heat up and the equipment does not perform as well. Reference to reliability criteria (7) indicates that even for non-military-specification-quality relays, one type of component in fare-collection equipment, a cycling rate lower than 1000 cycles/h will not cause a decrease in the individual part transactions per failure. However, a temperature increase from 25° to 47°C (77°-117°F) will cause a 20 percent increase in the failure rate. Conclusive data on this issue were not available for this paper, and the model used assumes a constant failure rate per rush-hour transaction.

Examination of even this model for the hypothetical case indicates the importance of high reliability levels. The number of simultaneous equipment failures increases at a much faster rate than the decline of equipment availability.

Queuing Model

Knowing the number of joint machine failures is a first approximation of the performance of the total system. It is possible to have conditions that lead to many public complaints even if several or all of the machines are working. A queuing model can develop more detailed information about these conditions.

The number of machines, their incidence of failure, the time it takes for them to be repaired, and passenger processing and arrival rates are all factors that affect queue length.

A standard multiple-server queuing model was used for illustration (8, p. 302). Such a model can be combined with the results of the equipment-availability model to indicate expected queue lengths and waiting times for varying numbers of machines in working order.

Table 5 illustrates the application of the model for a station with nine fare gates. Representative arrival and service rates were selected. The arrival rate was determined by assuming that 260 persons alight from a train and must be cleared within 2 min--that is, before the arrival of the next train.

The queuing model indicates that very long queues can be expected when fewer than six gates are operational. Based on the binomial distribution, this situation occurs with the existing equipment 4 percent of the time (A = 0.90).

With six gates in working order, there are at least 32 customers standing in queues. The mean time spent in the queue is about 15 s. The model also shows that the probability of a customer waiting for at least 30 s is 15 percent. The combined probability of a passenger waiting 30 s is the probability of six gates being in working order multiplied by the probability under this condition of a 30-s queue, or (0.04) (0.15) = 0.006.

These models show the type of operation that can be expected with varying levels of availability and therefore establish a planning tool for assessing the magnitude of the effect of a change in machine availability. Studies of this kind can be tailored to individual stations and various availability levels.

FARE-COLLECTION DEVELOPMENT NEEDS

Several fare-collection problems apply to all transit systems, whereas others apply to only a few. Problems with coin acceptors and bill validators--i.e., frequent jamming, wear, and acceptance of foreign coins and slugs--affect nearly every transit system. These devices are used in change makers and token sellers or as subsystems of vendors and turnstiles.

Transit properties are encountering increased public pressure for special fares, which their equipment, designed for flat fares, cannot handle. An automatic system to process these fares that complements rather than replaces the existing system is needed.

The data presented in this paper indicate that the reliability of recent AFC equipment designs must be substantially improved. Equipment security from internal and external fraud must also be improved and in a manner that does not significantly reduce reliability.

A reassessment of the concept of using magnetically encoded cards as the ticket medium may be worthwhile. This does not imply that those systems could not be made to work if properly

Table 4. Probability that x of nine gates will be operable.

Number of Gates Operable	A = 0.85	A = 0.90	A = 0.95	A = 0.975
3	-	-	-	-
4	0.004 99	0.000 83	0.000 02	0.000 001
5	0.028 30	0.007 44	0.000 49	0.000 04
6	0.106 92	0.044 64	0.006 61	0.001 13
7	0.259 67	0.172 19	0.057 17	0.018 85
8	0.367 86	0.387 42	0.288 53	0.183 75
9	0.231 62	0.387 42	0.647 17	0.796 24
	1.00	1.00	1.00	1.00

Table 5. Gate queuing analysis.

Item	Number of Machines Operating: 6	7	8	9
Avg queue waiting time (s)	15.40	1.33	0.41	0.15
Avg flow time (s)	18.18	4.11	3.19	2.93
Probability that a patron will wait more than x seconds to use a machine				
60 s	0.03	N	N	N
30 s	0.15	N	N	N
15 s	0.38	0.001	N	N
10 s	0.51	0.01	N	N
5 s	0.68	0.07	0.01	N
3 s	0.77	0.16	0.03	0.01
2 s	0.82	0.24	0.07	0.02
1 s	0.87	0.37	0.15	0.01

Note: N = negligible.
Service time = 0.36 customers/s; arrival rate = 2.10 customers/s.

specified and developed. However, superior alternatives may exist.

Tickets that are encoded in the form of electrically conductive inks, punched holes, or visible characters readable by both machines and people offer many possibilities. Some of these concepts are already in practice, e.g., in ticket cancelers, at certain parking-lot pass gates, and at supermarket counters.

The design of ticket vendors should also be examined. Several European manufacturers produce vendors that sell magnetically encoded tickets from a roll or a fan fold. This eliminates many of the problems associated with the hopper feeding of thin paper tickets.

The banking industry is developing concepts that could be applied to transit. The use of electronic funds transfer could reduce many of the problems with worn money. Use of more sophisticated coding techniques could greatly reduce the counterfeiting of cards and problems associated with high magnetic-tape bit density.

Farecard design is an area that could have a large impact on system performance. By varying the surface textures, coatings, and shapes of cards, jam rates may be significantly reduced.

Recent vendor designs have tried to reduce the workload in the central counting room by having the vendor perform a stacking function. The value of this policy should be examined, in light of the added costs of vendor reliability. Equipment to aid in the processing of large volumes of money is also required.

As in the rest of the transit industry, procedures or equipment designs for various fare-collection functions vary from one agency to another. Increased standardization might lower the costs of new equipment. Less ambitious fare-collection specifications might permit greater use at lower costs of upgraded products originally developed for the vending industry. Efforts to develop equipment specifications that could be used by several operators may be fruitful.

The need to develop automated equipment to process bus-rail transfers in a graduated-fare system is often cited.

Commuter railroads that charge distance-related fares offer the potential for a successful demonstration of self-service fare-collection techniques.

The cost of the fare-collection system is a hidden element of the construction costs of new rail transit lines. Huge increases in station costs are attributable to the need to provide mezzanines for fare-collection equipment. Techniques to reduce these costs should be investigated.

Fare collection represents between 7 and 31 percent of revenues collected. Operators might achieve large cost savings by means of research and development leading to the development and specification of more effective fare-collection systems.

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