Functional evaluation of the Los Angeles smart card field operational test

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Abstract

This paper summarizes the functional evaluation of an Advanced Fare Payment System deployed in Los Angeles in the summer of 1994. The functional evaluation is part of a larger Field Operational Test evaluation (Chira-Chavala, T., and Coifman, B., 1996. Impacts of Smart Cards on Transit Operators: Evaluation of I-110 Corridor Smart Card Demonstration Project. UCB-ITS-PRR-96-17, Institute of Transportation Studies, California PATH Research Report, University of California, Berkeley, CA; Guliano, G. and Moore II, J. E. 1996. Evaluation of the I-110 Corridor Smart Card Demonstration Project. UCB-ITS-PRR-96-20, Institute of Transportation Studies, California PATH Research Report, University of California, Berkeley, CA) managed by the Partnership for Advanced Transit and Highways (PATH) for the California Department of Transportation (Caltrans) and the Federal Transit Administration (FTA). The demonstration project fielded two types of advanced fare cards incorporating very different technologies on three separate transit properties as part of a relatively low cost system constructed from components manufactured to commercial rather than industrial specifications. Overall, the system performed well. Radio Frequency (RF) Cards demonstrated extremely high reliability. Smart Cards performed less well than the RF Cards, but both systems greatly surpassed the standards for magnetic stripe cards. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Smart card; Technology; Fare media; Transit; Field operational test (FOT); Evaluation; Partnership for Advanced Transit and Highways (PATH); Los Angeles

1. Introduction

A significant portion of the US transportation technology program is devoted to increasing the effectiveness and productivity of public transit. New technology has the potential to provide

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better information for transit marketing and planning, increase system efficiency, and better integrate alternative transport modes. Some of the most promising new technologies involve advanced fare media. This paper presents an assessment of the functional performance of two particularly promising advanced fare media, a Smart Card and a Radio Frequency (RF) card.

1.1. Advanced fare media

An advanced fare payment system includes a fare medium, some means of reading and altering the medium to reflect payment and system use, and some means of verification (Hansen et al., 1994, p. 10). Magnetic stripe cards are currently the most widely used advanced fare medium. They are in use on all of the "new generation" heavy rail transit systems (BART, MARTA, WMATA, Miami), on MBTA (Boston), and on several of the new light rail systems. These are most commonly debit cards. They have a relatively limited capacity to store information, although data can be read to and from the card. They are also subject to fraudulent use, since they are relatively easy to duplicate. In contrast, the Smart Card is a small computer. It contains a microprocessor and memory, and it reads and writes electronic information. It can store many thousands of characters, and communication of information can occur in a number of ways. It is difficult to duplicate, and is far more reliable than magnetic stripe cards. It therefore has far greater potential for accommodating a range of fare structures, for integration with other transit information and communications systems, and for streamlining the fare collection process. A Smart Card can require physical contact to establish communication, like a magnetic stripe card, or can be constructed as a Radio Frequency Card. Such RF Cards include both full function Smart Cards; and more specialized, lower function wired logic cards.

Smart Cards are likely to be made available for a combination of public and private transactions (Hornsby, 1994; Williams, 1994), including applications that combine transit and Electronic Benefits Transfers (EBT). However, introduction of new technology elements to general use requires that their performance be demonstrated. New technology must be physically durable, functionally reliable, user friendly, and appropriate to the designated tasks.

Smart and RF Card technology is the subject of a field demonstration that took place in Los Angeles during the summer of 1994 as part of the Federal Transit Administration’s Advanced Fare Payment Media Research and Development project. The Los Angeles demonstration is part of a multiphase, multiagency project aimed at developing an advanced transit fare payment system for commercialization. The physical conditions of the test present a standard transit environment that any fare card system must be designed to tolerate. The purpose of the demonstration is to test and compare two different fare card technologies with respect to the three objectives of performance, cost, and user acceptance; and to determine the field performance of a system constructed from commercial (rather than industrial) components. This paper focuses on the first two objectives.

1.2. Project overview

1.2.1. Purpose of the demonstration project

The system tested is constructed around the concept of a “passenger transaction system” (Echelon Industries, 1992) that can read, write, and store information and that can be linked to a
variety of subsystems. A full function passenger transaction system is far more than a new type of fare collection system. Available technology makes it possible to collect ridership information by vehicle location and time of day. Incorporating a Global Positioning System (GPS) into the system makes it possible to automatically charge distance-based fares, and to evaluate in-service vehicle performance. Thus the passenger transaction system adds greatly to transit management's ability to monitor and analyze service operations and passenger demand. Table 1 summarizes the characteristics and functions most likely to be associated with such a system. The characteristics and functions of the system fielded for the test is a subset of these.

1.2.2. Description of the demonstration project

The Volpe National Transportation Systems Center has defined a framework for evaluation of operational tests of Advanced Public Transportation Systems (APTS; Casey and Collura, 1994). Fig. 1 compares the framework prescribed by the Volpe Center to the relationships existing between the participants in the Smart Card Field Operational Test. There are minor differences in relationships existing between the project participants and Volpe recommendations, particularly with respect to the degree of autonomy afforded the system designer, but the test and evaluation was organized in a way mostly consistent with the Volpe guidelines.

The field operational test (FOT) included three transit agencies using two different card technologies. A contact-based Smart Card was tested on Route 1 of Gardena Bus Lines. A contactless RF Card was tested on Route 448 of Los Angeles Department of Transportation (LADOT) and Route 2 of Torrance Transit. The cards have very different capabilities, but can be programmed to operate equivalently as fare cards. The RF Card operates by passing within a few inches of a Passenger Interface Unit (PIU). The Smart Card operates via insertion into a slot in the Passenger Interface Unit. Power is delivered to the card through the contacts in the PIU. In addition to the Smart and RF Cards, the advanced fare system includes passenger transaction units (PTU) installed on buses, each linked to a GPS. The equipment is designed, procured, and installed by Echelon Industries.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A fare card that can be issued and recharged by a variety of means (e.g., through the transit agency, the employment site, or a clearinghouse), or via a telephone call</td>
<td>Integrate transit fare payment with other types of payments and subsidies (e.g., employer-provided rideshare credits)</td>
</tr>
<tr>
<td>A fare card that can record, debit, credit, and verify all passenger transactions</td>
<td>Charge distance-based &quot;needs-based&quot; fares</td>
</tr>
<tr>
<td>A fare transaction unit that is linked with a vehicle locator system</td>
<td>Monitor schedule adherence</td>
</tr>
<tr>
<td>A passenger boarding/alighting counting system</td>
<td>Develop a detailed data base of ridership characteristics</td>
</tr>
<tr>
<td>A video surveillance system</td>
<td>Improve security</td>
</tr>
<tr>
<td>A bus stop announcement system</td>
<td>Address Americans with Disabilities Act requirements</td>
</tr>
<tr>
<td>A transfer and receipt printing system</td>
<td>Improve data keeping</td>
</tr>
<tr>
<td>A vehicle monitoring system</td>
<td>Reduce transfer costs</td>
</tr>
<tr>
<td></td>
<td>Improve vehicle utilization</td>
</tr>
</tbody>
</table>
The FOT was located within the California Interstate-110 (Harbor Freeway) corridor. The I-110 extends south from downtown Los Angeles approximately 25 miles to the Los Angeles Port area. Each transit agency selected one route within the corridor for the demonstration. Gardena Route 1 provides local service through the City of Gardena, accesses the I-110 at El Segundo Blvd, exits I-110 at Martin Luther King Boulevard, and provides local service around downtown.
Torrance Route 2 provides local service through Torrance and Gardena, and then provides parallel service to Gardena Route 1. LADOT Route 448 is a peak-only route that serves commuters in the Palos Verdes and south Torrance residential areas. Route 448 accesses the I-110 at Pacific Coast Highway and also exits at Martin Luther King Boulevard, serving limited stops within downtown.

The most critical aspect of the project is functional performance testing. Project participants decided that discounts would be offered to provide an incentive for purchase and use of the card. Unfortunately, this discounting eliminated any possibility of examining the effect of the cards on transit demand.

Three hundred and fifty Smart Cards and 500 RF Cards were made available for purchase. On 1 August 1994, cards were activated for use and the onboard field test began; 241 cards had been issued. By September, all the Smart Cards assigned to Gardena were sold out. LADOT and Torrance continued to issue new RF Cards at this time. By the third week of September, as many as 508 cards had been issued by the three agencies. By November, a total of 36,000 fare transactions were completed using card technology. The demonstration ended in January 1995 with the withdrawal of the equipment from the vehicles. By the end of this 6 month period, as many as 594 cards had been issued, 536 of which were in use, and over 48,000 transactions were completed. Table 2 gives the number of buses equipped and cards issued for each transit agency and route.

2. Technical summary of the advanced fare payment system

2.1. System overview

The Advanced Fare Payment System Echelon Industries deployed for the test has the following elements.

1. Passenger Interface Unit: This card reading unit performs the fare transaction. The unit reads a specific type of card, including magnetic stripe, Smart, or RF Cards. It is also

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Equipment and cards tested by agency and route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route type</td>
<td>Gardena route 1</td>
</tr>
<tr>
<td>Number of buses assigned to peak service</td>
<td>Local and commuter</td>
</tr>
<tr>
<td>Number of buses equipped</td>
<td>8</td>
</tr>
<tr>
<td>Trips/weekday&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10</td>
</tr>
<tr>
<td>Card technology</td>
<td>Smart card</td>
</tr>
<tr>
<td>Number of cards used (and issued)</td>
<td>283 (322)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Daily one-way trips, excludes evening.
<sup>c</sup> Source: LADOT average daily ridership estimate.
designed to accommodate visual displays and speech messages. The Passenger Interface Unit is installed near the passenger side of the farebox, with the exact location varying by type and layout of the vehicle.

2. **Driver Interface Unit:** This unit is used by the driver to control and communicate with the system. It allows the driver to control the visual and sound displays of all units, to access various types of information (e.g., passenger counts by fare type, bus speed, location, and heading), and to process fare card actions. The Driver Interface Unit is mounted between the farebox and the steering wheel, with the exact location depending on the vehicle layout.

3. **Passenger Transaction Controller:** This unit performs data processing, data storage and input/output functions. The basic components include a 486/40 MHz central processor unit on a 8/16 bit ISA bus. It accommodates the fare transaction, vehicle location, speech messages, etc. The Control Unit is placed where space was available, usually in the radio compartment or behind the driver seat.

4. **GPS Receiver:** The Global Positioning Satellite receiver tracks the geographic location of the vehicle.

The Advanced Fare Payment System deployed for the test is summarized in Fig. 2. It is an abbreviated version of a larger scale Echelon Industries' Fare Transaction Vehicle Management/ Monitoring System (FareTrans VMS, Echelon Industries, 1995). A full scale FareTrans VMS provides considerable management information, including the identity of the card, the category of the card holder, the stop where the transit user boards the bus, the bus number, the route number, the number of riders on board the bus when the new boarding occurs, the exact location of the bus, the time of the boarding, and other related data. The information provided to the transit user includes system and stop announcements in the language associated with the identity of the card, visual announcements, and hard copy such as transfers and receipts. Short-range radio is used to read transaction and system performance data stored in the Passenger Transaction Controller when vehicles reach a designated location in the transit properties' maintenance facilities. This same communications system updates the data stored in each controller to include changes in the status of user accounts. A simplified block diagram of a full function Fare Transaction VMS is shown in Fig. 3. The FareTrans VMS accounts for most of the functions ascribed to a comprehensive Passenger Transaction System.

The Advanced Fare Payment System is designed to be expandable to a full function FareTrans VMS (Echelon Industries, 1995), but excludes a number of FareTrans VMS elements, including door sensors, language sensitive system announcements, mechanical performance sensors, some system redundancies, and radio update and retrieval of onboard data. Accumulated on-board data was updated and retrieved during the field test by the vendor via a hard-wire interface with each Passenger Transaction Controller. The field-test system accommodates a printer, but there was no substantive field testing of printing equipment.

### 2.2. Fare card technologies

The RF Cards and Smart Cards deployed for the test are consistent with the International Standards Organizations (ISO) standards for Integrated Circuit (IC) Cards, but are quite different in many respects. The Smart Cards are state-of-the-art, second-generation designs (Bright, 1988)
with sophisticated internal logic and operating systems capable of accommodating multiple debit accounts. The cards are intended for use as electronic wallets, combining extensive on-board memory and intelligence, and allowing fare transactions taking place in the field to be processed by the card.

The RF Cards have a much more limited information processing capacity than the Smart Cards. The RF Cards are wired logic cards that include a degree of dedicated intelligence, but cannot provide the range of applications available from a card-based central processing unit. In short, the RF Cards do not include the distributed intelligence of the Smart Cards. Instead, intelligence is concentrated in the card reader/writer units onboard the buses.
The RF technology is distinguished by the absence of a line of sight between the transponder and the reader. This provides the RF Cards used in the field test with the important advantage of being proximity cards: They do not require physical contact with the card read/write units to complete a transaction. From the users’ perspective, the RF Cards are a new technology for which few reference points exist.

2.2.1. Card industry standards

Table 3 provides a brief taxonomy of Integrated Circuit card characteristics. Definitions relating to card categories are imprecise and overlap, but the presumption of intelligence pervades the contemporary definition of a “Smart Card.” The functions of second generation Smart Cards imply a densely packaged integrated circuit of no more than 25 mm² (Russell, 1994) that includes
Table 3
Smart card taxonomy

Integrated circuit (IC) cards
- Satisfy broadest definition of “smart cards”
- Excludes other classes of memory cards:
  Magnetic stripe cards.
  Optical memory cards.

(1st Generation) IC memory only cards
- ISO: memory 1 Kbit, e.g., telephone cards.
- PCMCIA: memory 40 Mbytes.
- External read/write terminal.

Wired logic cards
- Memory 2KBytes, e.g., prepaid credit cards.
- External read/write terminal.

Includes RF cards deployed for the FOT.

(2nd Generation) smart cards
- 8-Bit microprocessor.
- Memory 8KBytes:
  EPROM (permanent).
  EEPROM (erasable).
- May incorporate DES or RSA Encryption.
- External read/write terminal.
  Includes Smart Cards deployed for the FOT.

Application Specific IC Cards (ASIC)
- Memory IC plus security and control logic.
- Memory 16 KBits.
- External read/write terminal.

(3rd Generation) Super Smart Cards
- Onboard or other nonterminal power source.
- Incorporates terminal I/O elements:
  keyboard
  display.

the microprocessor, arithmetic processing registers, random access memory (RAM) used during program execution, read only memory (ROM) to house the operating system, electronically erasable read only memory (EEPROM) for data storage, input/output, and an integrated operating system embedded in a credit card sized piece of plastic.

Table 3 combines information from multiple sources (Bright, 1988; Seidman, 1993a,b, 1994; Krueger, 1994) that are not entirely consistent, and is merely suggestive in light of rapidly evolving technology. Mitchell (1993) and Lisimamique (1994) provide detailed physical specifications for Smart Cards representative of the contact card technology deployed in the Field Operational Test.

2.2.2. Fare cards deployed for the field operational test

The contact-based Smart Cards fielded on Gardena Line 1 incorporate PCOS (Echelon Industries, 1995), an advanced propriety operating system designed to support bank card debit transactions. The RF Cards tested on Torrance Line 2 and LADot Line 448 and do not use EEPROM to store user data. Instead, these RF Cards use Ferromagnetic Random Access Memory (FRAM), a propriety technology applied under license that provides faster read/write cycles, requires low power, and offers the high packing density of Dynamic Random Access Memory (DRAM, approximately 3 to 6 times the density of EEPROM). In addition, RF cards
can be either active or passive (Vossel, 1994). Active cards include a battery. Passive cards obtain energy for transmitting identifying information from a burst sent to them from a reader/writer/interrogator units. The RF Cards deployed in the FOT are passive.

Table 4 provides a summary comparison of the Smart and RF Card technologies deployed in the Field Operational Test. The vendor retains propriety rights to the detailed design of the systems implemented. Giuliano and Moore (1996) provide a more detailed summary of the basic data exchange characterizing Smart and RF Card transactions. Boarding and alighting times greatly exceed transaction processing times. Summary time study of boarding operations during the FOT is reported by Chira-Chavala and Coifman (1996). If more extensive on-board database checking and updating associated with a full Function FareTrans VMS is added to the system, then the additional processing burden associated with these activities will increase transaction time requirements, possibly to the point of affecting boarding times, especially if fare cards are in wide use.

3. Functional analysis

Functional analysis measures system performance. Evaluating the system’s performance requires an examination of system capabilities and performance expectations, and comparison of outcomes against benchmarks provided by design performance characteristics and industry standards. System malfunctions, card failures, and other problems must be identified, characterized, and explained.

The most general level of functional analysis combines field test data with reliability theory to provide parametric estimators for the Mean Time To (system) Failures (MTTF) and an Increasing Failure Rate (IFR) distribution used to describe changes in system reliability over time (Bentley, 1993; Hillier and Lieberman, 1995). The state of information necessary to meet this ideal standard is very refined. The narrow scope and relatively short duration of the test does not permit this preferred level of parameterization. However, it is still possible to assess the system’s performance, and to identify important technical opportunities and constraints.

A key objective of the demonstration project is to design a system that could be sold profitably to transit agencies for less than $10,000 per bus. Consequently, it was necessary to use a modular design and readily accessible, off-the-shelf hardware and software components manufactured to commercial specifications. The operating environment of a public transit bus may be more rugged than commercial components are designed to withstand, and the reliability of commercial components in such a quasi-industrial environment was an open question of central importance. The two most important technical questions revealed during the course of the test relate to:

1. management of RF Card transaction speeds, and
2. the effects of humidity and static discharge on contact-based Smart Cards.

3.1. Data resources and constraints

It is difficult to isolate sources of failure in a successful project. Success in the field is encouraging from a scientific and commercial perspective, but low failure rates constrain the number of
<table>
<thead>
<tr>
<th>Card technology</th>
<th>User interface</th>
<th>Intelligence</th>
<th>Erasable memory</th>
<th>Power source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart</td>
<td>Contact based</td>
<td>Concentrated on the card</td>
<td>8 KBytes of Electronically Erasable Programmable Read Only Memory (EEPROM)</td>
<td>ISO compliant.</td>
</tr>
<tr>
<td>International Standards Organization (ISO) international series 7816</td>
<td>Similar to magnetic stripe cards</td>
<td>Card IC includes an 8-bit micro-processor</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>External red/write unit required for transaction processing</td>
<td>Approaches the upper bound of 2nd generation design. Some cards have 16 Kbytes</td>
<td></td>
<td>Contacts permit transfer of data and power from the read/write unit.</td>
</tr>
<tr>
<td>Radio frequency (RF) identification</td>
<td>Contactless</td>
<td>Shared between the card and the red/write unit</td>
<td>256 Kbits of Ferromagnetic Random Access Memory (FRAM)</td>
<td>Card antenna collects radiant energy broadcast from the read/write unit. Requires no battery.</td>
</tr>
<tr>
<td></td>
<td>No comparable mass consumer product</td>
<td>Card IC capable of wired logic only</td>
<td>Propriety memory technology with very fast read/write operations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proximity access/ID cards provide comparable experience</td>
<td>External read/write unit required for transaction processing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
new lessons learned about the technology being tested. Data constraints associated with the test include the following.

1. RF card failures are rare.
2. Contact Smart Card failures are less rare, but remain infrequent.
3. Other equipment failures have been rare.
4. Equipment designs and manufacturing strategies are proprietary information not subject to independent review.
5. The test was relatively short in terms of life cycle requirements.
6. And, learning occurs throughout the test on the part of all participants.

The most important data source consists of transaction errors, nontransaction events, and the circumstances in which they occur. Type I errors occur when intended fare transactions do not take place. The test introduces multiple sources of type I errors, including failures associated with:

1. the information processing capacity of the Smart or RF Cards,
2. the data storage capacity of the Smart or RF Cards,
3. other components in the Advanced Fare Payment System, and/or
4. an inability of a user to successfully negotiate the system interface.

Type I errors may create the impression the system is unreliable, but also usually imply that the user rides without paying a fare. Type II errors are unintended transactions, usually multiple transactions occurring almost simultaneously. Type II errors present the possibility of a loss of user resources, and thus transit users are likely to regard type II errors as more onerous than type I errors. Consequently, avoiding type II errors is of great importance for promoting user acceptance. Overall, user acceptance of the test system was quite high. Users regarded the system as reliable (Giuliano and Moore, 1996). This indicates particularly successful management of type II errors.

From a functional perspective, less is learned from type II errors than from type I errors, because multiple transactions only occur when the capabilities of the system are mostly intact. Avoiding type II errors is more a matter of system management than appropriate technology. Type I errors occur when the system is failing to process intended transactions. Diagnosing these sorts of failures identifies problems that need to be corrected. These problems might, like type II errors, be a function of system management; or they might have other sources, including component failures, or errors in design, implementation, or technology choice. Even if the frequency of type II errors is sufficiently well controlled to ensure user trust, type I errors will remain of practical concern to transit properties because fares are foregone when type I errors occur.

3.2. Card performance

A summary of transaction errors occurring during the field test appears in Table 5. The test includes approximately 48,000 fare transactions during more than 35,000 h of bus service. The RF Cards perform reliably enough to be used as transit fare media. The Smart Card transaction success rate of 99.9% is equivalent to one failure per thousand, which is unacceptable for revenue
Table 5
Summary of FOT transaction errors

<table>
<thead>
<tr>
<th>Card type</th>
<th>Number of transactions</th>
<th>Type I errors</th>
<th>Type I errors per 1K transaction</th>
<th>Type II errors</th>
<th>Type II errors per 1K transactions</th>
<th>Success rate: undistressed cards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart Card</td>
<td>24,564</td>
<td>13 cases of defective cards</td>
<td>0.54</td>
<td>0 cases of multiple transactions&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.00</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 cases of data corruption</td>
<td>0.45</td>
<td></td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 cases of distressed cards</td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Card</td>
<td>23,416</td>
<td>2 cases of defective cards</td>
<td>0.08</td>
<td>10 cases of multiple transactions&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.43</td>
<td>99.99%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 cases of data corruption&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.81</td>
<td></td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 cases of distressed cards</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic Stripe Card</td>
<td>n/a benchmark only</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>85–93%</td>
</tr>
</tbody>
</table>

<sup>a</sup> RF Card data corruption is not classified as an error. The cards are easily reinitialized in the field. Data corruption in Smart and RF Cards can almost always be avoided by providing memory back-ups onboard the card. No memory back-ups are in place in the field test.

<sup>b</sup> This count is lower than the value reported by Echelon Industries (1995, Exhibit 5). Frequencies in the data corruption and multiple transaction categories may not be mutually exclusive. Echelon Industries is unable to provide electronic records of card transactions concerning type II errors.

<sup>c</sup> Smart Card transactions require that the card be inserted in the Passenger Interface Unit. The degree of attention required, combined with travelers' likely experienced with magnetic tripe cards, make type II errors highly unlikely.

service. The number of transactions processed on a major urban transit system can easily approach exceed one million per day. The loss of a thousand fares per day and the resources needed to rectify errors is not cost effective.

3.2.1. Learning

As noted above, learning affects the rates at which errors occur. Improvements are most rapid in the earliest stages of system deployment. The field test suggests system performance is influenced by learning on the parts of:

1. the technology vendor,
2. management of the participating transit properties,
3. bus drivers, and
4. card users.

This is consistent with the assumptions underlying learning curve analysis (Belkaoui, 1986). Parameterization of learning curves provides a means of projecting improvements in system performance and productivity as a function of experience.
Several similar function forms are used to specify learning curve relationships, but the most pervasive specification incorporates the assumption that relative improvements in productivity are a constant as experience increases. This implies a mathematical power function of the form

\[ g = K \cdot X^n \]  

(1)

where

\[ g = \] the resources required to produce the Xth unit,  
\[ K = \] the resources required to produce the first unit,  
\[ X = \] cumulative output,  
\[ f = \] the learning rate parameter,  
\[ 1 - f = \] the progress rate parameter, and  
\[ n = \log_{10}/\log_{10}2 = \] the learning index.

The progress rate parameter is the proportionate change in the left hand side of the equation as cumulative production doubles.

Learning curve analysis is premised on the assumption that experience with standard operations improves efficiency and reduces the frequency of errors. Improvements in efficiency are conventionally tracked by reductions in production costs, in part because this sort analysis emerged from the accounting literature. However, since learning reduces the likelihood of both type I and type II errors, it is feasible to relate the influence of cumulative transactions to changes in error rates instead of costs. Eq. (1) is estimated for type I errors occurring in the use of Smart Cards due to card failure and/or data corruption, and for type II errors occurring in the use of RF Cards. Results appear in Fig. 4. Type II errors consist of multiple fare payments when only one transaction should occur.

About 60% of the observed type I errors in Smart Card use persists as cumulative experience doubles. About 51% of the observed type II errors in RF Card persists as cumulative experience doubles. The coordinates in Table 4 are monthly averages computed across thousands of transactions per month. Thus each coordinate provides substantial information. Given the large size of the transaction sample and the low frequency of errors, these estimates are highly significant.

3.2.2. Data corruption

Data corruption was the most pervasive source of transaction failures during the test. No back-up memory records exist on either type of card. This is an intentional aspect of the test intended to provide a better comparison of the two technologies, and to better illuminate the events leading to data corruption.

Data corruption occurs for different sets of reasons across the two types of cards. One source of data corruption is interruption of read/write cycles, which is more likely in the case of RF Cards than for contact cards. However, the Smart Cards are more complex devices designed to deliver a wider range of services, and the complexity of the card provides more opportunities for data problems.

RF Cards subject to data corruption could be reset in the field and returned to service. RF Card failures that cannot be corrected in the field were extremely rare in this field test. Table 5 reports that only two RF Cards failed to this degree in almost 24,000 transactions. The likely
Fig. 4. Estimated learning curve model of changes in Smart Card type I error rates; and in RF Card type II error rates.
sources of severe RF Card malfunctions include manufacturing defects, or broken internal contacts leads due to incidental flexing. The two failed RF Cards were not returned to the manufacturer for analysis because the number of failures was much lower than the RF Card production specifications.

Data corruption in Smart Cards is more problematic, because Smart Cards cannot be reinitialized as routinely as RF Cards. After testing several inoperative cards, the card manufacturer provided the vendor with software capable of unlocking some of the cards and returning them to service.

Transaction failures of any sort provide users with compelling disincentives to use automatic fare payment systems. Providing back-up data records on the card provides a path around data corruption events, and allows immediate field recoveries when data corruption occurs. The frequency of data corruption indicates that commercial deployment must include redundant data sets. This is standard practice in the industry.

3.2.3. RF Card lock-out periods

The RF Card uses Ferromagnetic Random Access Memory (FRAM) technology instead of the Electronically Erasable Read Only Memory (EEPROM) typically used in Smart Cards. FRAM is the fastest memory technology currently available commercially, with a theoretical floor of about 75 ms for fare transactions of the sort processed during the field test. The minimum achievable transaction time in the demonstration ranges from 90 to 104 ms. This reflects other design limitations inherent to the RF Cards. The design target is 250 ms.

Given such rapid processing, multiple transactions are inevitable for a proximity card unless steps are taken to preclude them. In addition, the novelty of RF Card technology may tempt travelers to conduct casual experiments by exposing the card to the card reader/writer's field multiple times. By briefly precluding any subsequent transactions each time a transaction occurs, the risk of multiple transactions is greatly reduced. A lock-out period of 6–7 s following transactions reduces the likelihood of multiple transactions to nearly zero.

3.2.4. RF Card transaction interruptions

Memory speed is one of several factors affecting transaction times. Other considerations include:

1. processor speed,
2. internal card organization, and
3. the read/write operations associated with the transaction.

Even if multiple transactions are precluded by a lockout period, the probability of interruption increases with longer transaction periods. Users might inadvertently remove a card before a long transaction is complete.

The initial absence of a lock out period during the test makes it possible to estimate the likelihood of interruption as a function of transaction processing time. Electronic records of R-F Card nontransaction events determine where in the card's information cycle interruption occurs. In addition, the vendor intentionally extended the time required for some transactions. A qualitative assessment of the vendor's findings appears in Fig. 5, which describes the relationship
between the probability of a transaction interruption and time required to complete a transaction. At 250 ms, the probability of transaction interruption is under 0.05.

3.2.5. Smart cards and humidity

Table 5 identifies 13 defective Smart Cards for which the failure mechanism is unknown. The most important way that the RF and Smart Cards differ in use is that the Smart Cards require physical contact with a reader/writer. Physical contact introduces the possibility of static electric discharge, which might interfere with the operation of the cards. Low humidity levels increase the likelihood of static discharge, and thus humidity is a candidate explanation for the higher incidence of Smart Card failures.

A summary of humidity levels and fare card problem report logs appears in Fig. 6. The Smart Card complaints logged during the test identify 38 card failures not clearly due to physical distress of the card. This number exceeds the 24 cards accounted for by Echelon Industries vendor. Presumably, the 24 cards classified by Echelon as "defective" or subject to "data corruption" are included in this set of 38, as must be some of the cards identified by Echelon as "distressed." Cards identified as "distressed" have been subjected to visible damage.
Fig. 6. Humidity levels and transactions vs Smart Card failures.
Careful investigation of humidity effects requires a comparison of the estimated likelihood of card failure against humidity levels. Cards labeled “defective” are of greatest interest. Unfortunately, the card manufacturer declines requests to fully classify the status of failed cards with respect to data corruption. There is no way to know exactly which failures are known to involve data corruption and which are due to other effects. Total counts are known, but the cards labelled “defective” and subject to “data corruption” cannot be isolated within the set of 38 failures.

The upper and lower bands shown in the lower portion of Fig. 6 are smoothed polynomial regressions of the humidity bounds observed during transit service hours. The center band is the smoothed sequence of weighted average humidity levels during service hours. Smart Card failures are concentrated in September and the first half of October, yet Fig. 6 indicates these are not particularly dry months. There is greatest variance in the minimum humidity levels recorded during the Fall, but maximum humidity levels in Los Angeles are as high during the Summer as they are in the Winter. The period from the second half of October through November is the driest, yet card failures are not most frequent during this period. Failures diminish rapidly during December and January, but this could be due to a number of factors. Wetter conditions may reduce the likelihood of card failures, inclement weather may be suppressing travel, or card use may be reduced as the conclusion of the test nears and cards cannot be renewed.

The simplest mechanism for investigating the association between humidity and the likelihood of card failure is a contingency table. Ranking daily humidity levels summarized in Fig. 6 establishes humidity intervals. Daily card use is estimated based on weekly transactions summaries. Any sufficiently pronounced degree of association between humidity and failures will permit the null hypothesis:

\[ H_0: \text{ No structural association between humidity levels and failure rates to be rejected.} \]

Unfortunately, the alternative hypothesis for this test is very general,

\[ H_1: \text{ Not } H_0. \]

Contingency tests are inconclusive with respect to the influence of maximum humidity, minimum humidity, and humidity range on the frequency of card failures. In all three cases, the null hypothesis cannot be rejected at any conventional significance level. However, as shown in Table 6, the null is rejected at the 0.05 level if failures are classified by weighted average humidity during the transit service interval. The \( p \)-value for the test is approximately 0.017, indicating that the null hypothesis can almost be rejected at the 0.01 level. Unfortunately, since the cards combine

<table>
<thead>
<tr>
<th>Number of transactions</th>
<th>23–50%</th>
<th>50.1–70%</th>
<th>70.1–75%</th>
<th>75.1–80%</th>
<th>80.1–97%</th>
<th>Row Σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>3441</td>
<td>5320</td>
<td>4270</td>
<td>5850</td>
<td>5682</td>
<td>24,564</td>
<td></td>
</tr>
<tr>
<td>Reported card failures</td>
<td>9</td>
<td>4</td>
<td>11</td>
<td>9</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td>Expected smart card failures</td>
<td>5.323</td>
<td>8.231</td>
<td>6.606</td>
<td>9.049</td>
<td>8.790</td>
<td>38</td>
</tr>
<tr>
<td>Chi-square statistic</td>
<td>1.346</td>
<td>1.268</td>
<td>6.189</td>
<td>0.0003</td>
<td>3.814</td>
<td>12.617</td>
</tr>
</tbody>
</table>

\[ \text{Critical value: } \alpha = 0.10, \text{ 4 df } \Rightarrow \text{ Reject } H_0, \text{ } 7.779 \]

\[ \text{Critical value: } \alpha = 0.05, \text{ 4 df } \Rightarrow \text{ Reject } H_0, \text{ } 9.488 \]

\[ \text{Critical value: } \alpha = 0.01, \text{ 4 df } \Rightarrow \text{ Failure to reject } H_0, \text{ } p\text{-value } 0.017, \text{ } 13.227 \]
at least two sources of failure, the test provides no definitive information about relationships
between humidity levels and failure mode. The largest contribution to the value of the test sta-
tistic is provided by outcomes associated with the midrange of observed humidities, in which case
failures are more frequent than expected, but there is no obvious, monotone pattern in the dif-
fences between observed and expected card failures.

If any relationship exists between humidity and Smart Card operations, it is complex, or
obscured by the aggregate nature of the data. Given the conditions of the test and nature of the
data, we cannot determine if the relatively lower reliability of the Smart Cards is a function of
their complexity, the fact that they are contact-based, or both. The manufacturer has declined to
share its own findings concerning the nature of card failures. However, given the disparity in the
performance of Smart and RF Cards in the field test, the modest statistical evidence supporting
humidity effects on Smart Card function suggests the role of humidity merits further investiga-
tion. The next phase of this test includes deployment of a full function FareTrans VMS across
several transit properties in Ventura County. This system incorporates a proximity Smart Card,
combining intelligence and RF communication. Comparing the results of the current and next
phases of the test will provide more insight into the reliability implications of using a contact-
based card.

3.3. Bus equipment performance

The vendor and the transit properties documented only 10 equipment problems during the
course of the test that were serious enough to interrupt revenue use of the cards. Consequently,
equipment failures provide only anecdotal evidence concerning the failures likely to occur during
long-term deployment. The combined impact of these incidents is reported by the vendor to be
just under 33 vehicle h. Combined repair time is reported to total less than 1 person h.

This near constant successful operation provides little insight into unanticipated design con-
straints. Installation requirements for the Passenger Interface Units, Driver Interface Units, and
Passenger Transaction Controllers are largely a function of the space constraints associated with
different vehicle configurations. The vendor worked closely with the transit properties involved to
select appropriate equipment locations in each of the thee bus types involved in the test. The
special equipment requirements associated with the test presented problems for properties that
routinely rotate buses across lines and runs. But this test constraint disappears if the card reader/
writers are standard equipment across vehicles within a given property.

The Geo Positioning System performed less well than the fare transaction equipment. The
reasons include peculiarities in the vendor firmware and undocumented aspects of data reading.
Updated firmware and new system software provided by the manufacturer remedied these pro-
blems.

Only one type of bus equipment problem was observed more than once. Disconnected cables
were encountered twice early in the test. Securing the cables provided a permanent solution. Only
one Passenger Interface Unit failed in use. The failure is attributed to corruption of the Com-
plementary Metal Oxide Silicon (CMOS) memory element of the transaction unit’s Basic Input/
Output Operating System (BIOS). CMOS BIOS corruption is frequently related to the battery
used to maintain the contents of the BIOS memory. Subsequent versions of the system will use
EEPROM to perform the BIOS memory function, circumventing potential battery problems.
Failure of a Passenger Transaction Controller's power conditioning subsystem is attributed to an undocumented accident during routine maintenance. The nature of this event and the mechanism by which the subsystem was destroyed are unknown, and thus there is no design response available. A problem with one of the Driver Interface Units is attributed to repeated exposure to water and resulting damage, and all problems with the driver and passenger interface units are attributed to either driver or passenger experimentation with the equipment interfaces, or to unobserved acts of vandalism.

4. Conclusions

4.1. Test results

4.1.1. Findings

Key findings from the functional analysis of the Advanced Fare Payment System are as follows.

1. The electromechanical performance of the bus equipment deployed for the field test shows it is feasible to construct the Advanced Fare Payment System almost entirely from relatively low cost commercial components, and to use the system to process fares in regular service on a public bus. This opportunity presents vendors with considerable latitude for constructing competitive, low cost systems.

2. The RF Cards performed extremely well, meeting or exceeding all performance standards associated with the application. Lock-out periods following transactions should be imposed to prevent unintentional multiple transactions. Data redundancies standard in the industry should be in place when advanced fare media are placed into regular revenue service.

3. The Smart Cards performed very well relative to magnetic stripe cards, but demonstrate a failure rate likely to be unacceptable in a transit context. Bus drivers process so many transactions that any fare payment system must be extremely reliable to add value to the operation. Even with redundant data backups, the frequency of the remaining Smart Card type I errors observed in the field test is likely to be too great to be acceptable.

4. Performance of the system improves over time in a measurable way. Transit agencies fielding similar systems can expect similar results if their processes are under control. Implementation of the RF Card transaction lock-out period is an excellent example.

5. The test data provides evidence of a humidity effect that is presumably related to static discharge, but this is not conclusive. If some of the type I errors associated with Smart Cards are related to static discharge, then these can be alleviated by using radio communication instead. However, smart Cards subject to unknown failure mechanisms, data corruption, and physical distress cannot be classified at the level of detail needed to verify a humidity effect. This classification can only be provided by Smart Card manufacturer.

4.1.2. Unanswered questions

The most important unanswered question relates to lifecycle performance. The equipment is in service during the field test for only 6 months, and performs well in this window. Results are in
every way encouraging, but the short duration of the field operational test and the infrequency of component failures provides no substantive information about lifecycle costs.

The proprietary nature of the system precludes review of detailed cost data. Price ranges for the most complex card configurations demonstrate considerable variance, even for very large production runs. Simple IC memory cards might be purchased in large batches for an unit price under $1. The addition of a microprocessor to a card with modest memory would be expected to multiply unit price by a factor between two and three (Seidman, 1994).

4.2. Generalizations

4.2.1. Advanced fare payment systems

A full function Fare Transaction/Vehicle Monitoring System (FareTrans VMS) will necessarily involve a more extensive set of read/write activities than the Automatic Fare Payment System deployed during the test. The flexibility provided by a FareTrans VMS permits collection of market data, highly differentiated fares (zone and area based fares, route and time of day pricing, special event and special user fares); intermodal transfers; automatic verification of card status and updates of fare accounts (which might include negative balances); electronic benefit transfers (EBT); integration with corporate transit, rideshare, and parking plans; and other functions.

Regardless of the intelligence vested in the fare card, executing these functions will require extensive database searches and updates by the Passenger Transaction Unit. Even the Automatic Fare Payment System deployed for the FOT might have eventually become subject to a substantial data burden as transactions are checked against lists of lost or stolen cards, or as more cards are automatically renewed in use. In full scale deployments, the definition of a transaction will likely have to be segmented in more sophisticated ways. Processes such as database searching need to be treated distinctly and optimized by algorithms separate from the procedures executing during the remainder of transactions.

4.2.2. Evaluation of field operation tests

Effective evaluation requires commitments on the part of project participants. The objectives of both the test and the evaluation should be accepted by the project participants, and achieving these simultaneous objectives should be a priority for all concerned. The test and the evaluation are not separable efforts. The test should be designed in a way that supports evaluation, and the evaluation should not inhibit the objectives of the test. Conclusions and learning depend on both a successful test and a successful evaluation.

A better and more comprehensive evaluation of this field operational test would have been possible had the evaluation team been available to participate in the test design. Closer coordination of data gathering efforts by technology partners and evaluators would permit more complete parameterization of human factors and systems engineering relationships. This is of particular importance with respect to short-term deployments. In the case of this FOT, the systems reliability elements of the evaluation would have been improved by co-designing the test and the evaluation to make more intensive use of the transactions data processed by the technology vendor.

Effective participation of the evaluation team is also related to timing. The evaluation contract was not funded until several months after the FOT began, and therefore the research team did
not attend many of the early meetings. The “before treatment” conditions are usually important for evaluation. Field Operational Tests that are intended to improve any aspect of system performance require the establishment of an appropriate baseline. In this case, much of the evaluation could be done from cross sectional observations, and there was adequate time for the “before” data collections required for the transit agency impact analysis.

Finally, we must note that the resources made available for federal sponsored field operational test evaluations are generally not sufficient for a thorough evaluation. Given the enormous amount of resources being invested in new technology development, investments in careful evaluation of new technology tests are surely cost-effective.

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