Primer on Electronic Toll Collection Technologies

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A comprehensive review of electronic toll collection (ETC) systems and related issues is presented with the primary purpose of providing transportation professionals with the basic knowledge necessary for the selection, evaluation, and implementation of various ETC systems. In addition, a tentative framework is offered for demonstrating, testing, and evaluating the performance of ETC systems. Many agencies are expected to procure ETC systems in the near future, creating a clear need for developing a standardized evaluation procedure. Once developed, this procedure can be used to demonstrate the capabilities of various systems and allow the results to be transferred among agencies.

The purpose of this article is to present a review of current designs, as well as developments in and implementation of electronic toll collection (ETC) technologies. ETC is based on vehicle-roadside communication systems; more precisely, it is an application of electronic signature detection to passenger and commercial vehicle traffic for the purpose of collecting tolls. ETC technology is part of automatic vehicle identification (AVI), a functional area of intelligent transportation systems (ITSs). [For a description of the systems approach to ITS, including a discussion of user services, functions to support these services, and technologies that provide certain functions, see Yablonski (*1*).] ETC allows drivers to pay tolls without stopping and can potentially generate significant economic and environmental benefits.

Because of the proprietary nature of ETC technologies, the limited information available about them comes from trade brochures and presentations at specialized trade conferences. These scant resources are not enough. Transportation professionals need to become more knowledgeable about ETC systems. The primary motivation for writing this article is to synthesize the available information, organize it, and present it to the transportation community, thus framing a "breathing document" that will evolve as the technology develops.

This article has two objectives. The first is to present a comprehensive review of ETC systems and related issues. The second is to offer a tentative framework for demonstrating, testing, and evaluating the hardware and functional performance of ETC systems.

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BASIC STRUCTURE OF AN ETC

An ETC system, shown in Figure 1, consists of a vehicle with an on-board unit, a two-way microwave link, and roadside (or tollgate) equipment. The in-vehicle equipment is a transponder, which is usually a tag, an integrated circuit (IC) card with a card holder, or a combination of the two. It stores the information needed for toll transactions, such as vehicle type, account identification, balance, etc. The roadside equipment consists of (a) transceiver (transmitter and receiver) or reader and decoder, the main functions of which are to verify the functionality of the in-vehicle equipment and to conduct the transaction; (b) a lane controller, which monitors activities occurring in a toll lane; and (c) a primary processing computer system, used to access account information and process the transaction requests. A schematic diagram of a generic system is shown in Figure 2. This paper describes the system in which a connection between the in-vehicle and roadside units is established via mobile telecommunication techniques primarily, a microwave or radio frequency (RF) link.

Transaction Process

A typical ETC transaction, shown in Figure 3, starts with the roadside equipment continuously sending interrogating signals via an antenna to the toll lane. This is the transmission phase, in which digital data received from a computer are used to modulate a microwave (or RF) carrier signal, which is then sent by the transceiver to the in-vehicle equipment via a downlink.

When a moving vehicle enters a communication area, its in-vehicle equipment unit receives the interrogating (wake-up) signal. The unit then sends an answering signal back to the transceiver via an uplink. This signal usually consists of elements of the unit's memory (vehicle identification, account number, balance, etc.). Sophisticated units may also have a security mechanism to prevent unauthorized access.

The transceiver receives the answering signal in the so-called reception phase. The roadside unit first verifies its data integrity by checking an error detection and correction code. If an error is detected, the transceiver repeats the interrogation. This process is repeated several times while the moving vehicle is in the communication range. The successfully completed process is referred to as a "handshake." The signal is demodulated to a digital signal (binary data) and sent to the processing computer. The computer deducts the toll from an account and sends this information back to the vehicle via the transceiver. The in-vehicle equipment then sends a signal back confirming that the information was successfully recorded. The process is concluded by the transceiver's reading of the content

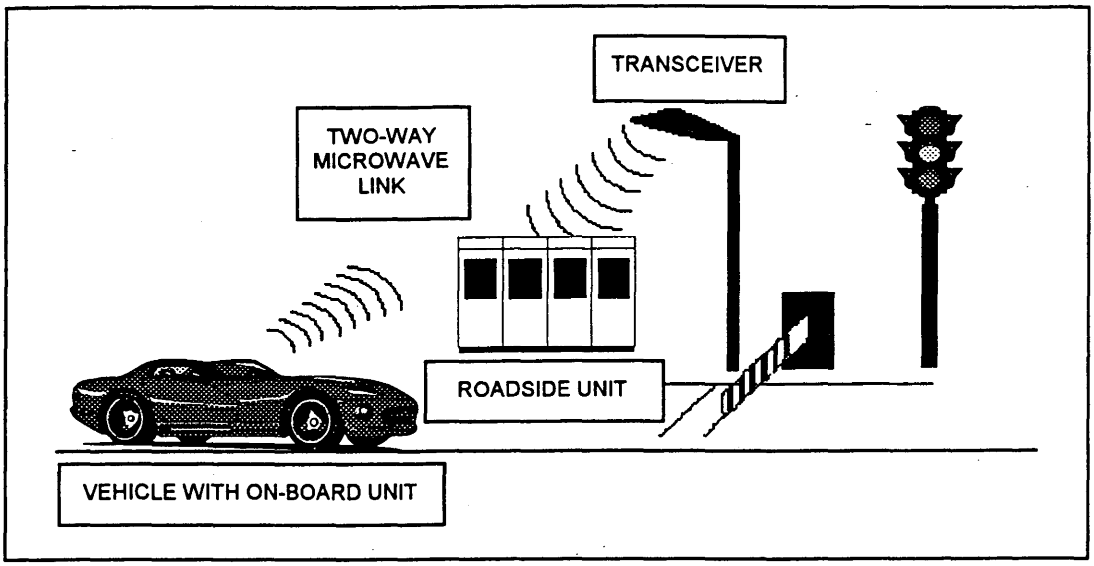

FIGURE 1 ETC system.

of the in-vehicle equipment's memory to verify that the appropriate toll is indeed deducted.

The solid lines in Figure 3 connecting processes represent a normal transaction. The dashed lines represent a transaction in which errors (both in RF communication and insufficient funds) are encountered, and the way the system responds by activating violation enforcement systems (VES).

The above process represents an "open" system operation, in which each time a vehicle passes a toll lane, the roadside unit instructs the transceiver to debit the vehicle's account. The transaction process is more complex when a vehicle enters a "closed" ETC system. At the point of entry, a roadside transceiver reads the memory content of the in-vehicle equipment unit. The computer then verifies the vehicle identification and account number, and whether sufficient funds are available in the account. The transceiver then writes a date, time, location, and lane number "stamp" in the appropriate fields of the unit's memory. When the vehicle exits the system, the transceiver reads the on-board unit's memory and the computer calculates the toll and debits the vehicle's account. This information is then written back to the unit's memory.

Antenna Types and Location

The entire ETC transaction occurs while a vehicle is traveling through a coverage area. The length of the area and the communication distance are determined by the receiver sensitivity, antenna type, location, and transmitted power. The distance is usually no longer than 40 m (137 ft) (*2*).

RF or microwave transmission uses antennas in both the in-vehicle and roadside equipment. In the in-vehicle equipment, the antenna is integrated within the equipment itself and has to be compact. In the roadside equipment, the antenna is installed at the toll plaza. Different manufacturers have different antenna configurations. Some use only one antenna for both triggering (sending an interrogating signal) and communicating, whereas others have sep-

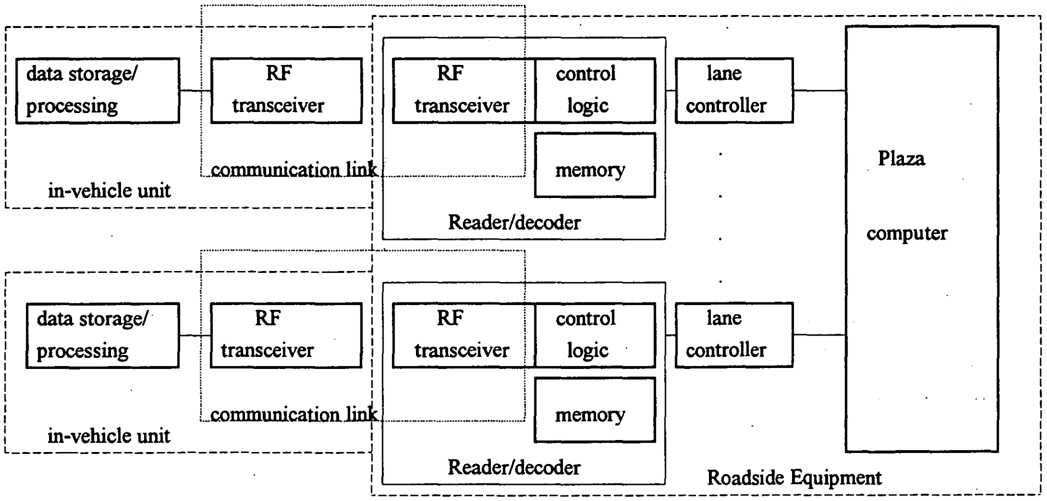

FIGURE 2 Schematic diagram of generic ETC system.

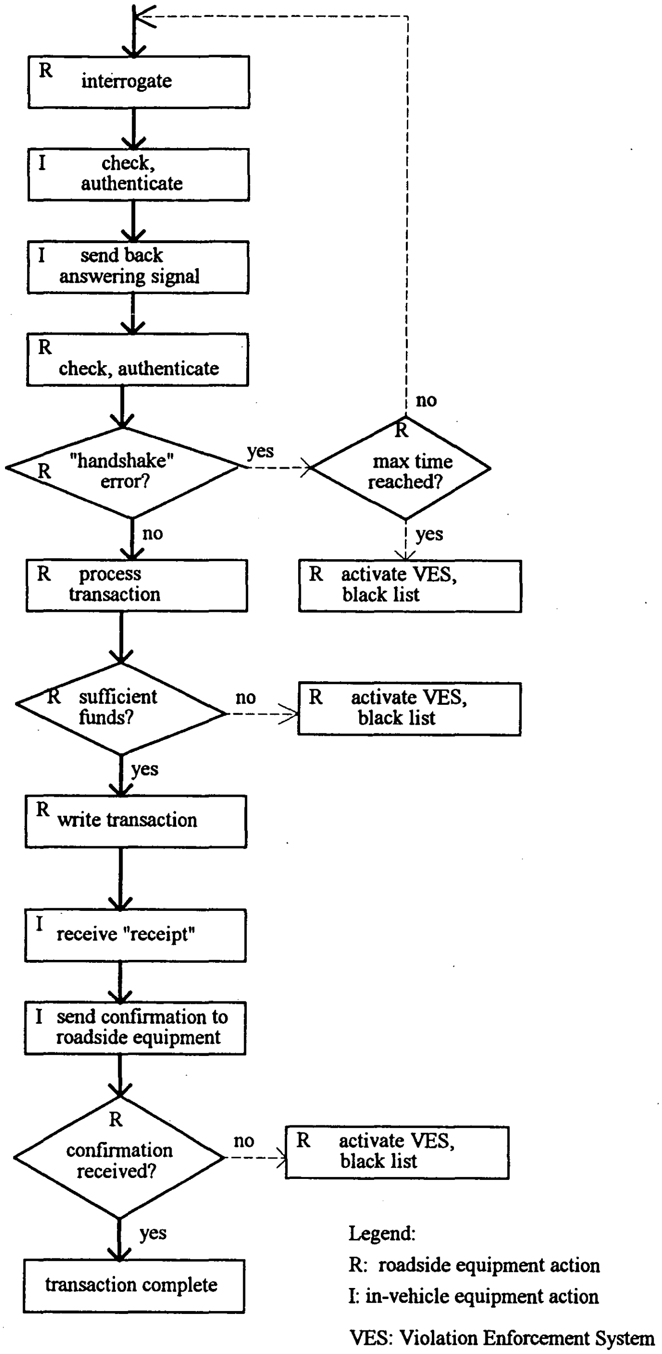

FIGURE 3 ETC transaction process.

arate antennas for each function. Still others have three antennas, one for triggering, one for communicating, and one for collecting position information to adjust the RF power output level or adjust antenna propagation patterns to optimize communication.

In terms of location, there are three kinds of antennas: in-pavement, distributed overhead, and focused beam. When one antenna is used to read multiple tags over multiple lanes, it is called a multiplexing antenna. Antenna selection is closely related to the frequency used, communication distance, and properties of the in-vehicle unit.

TAG AND IC CARD–BASED ETC SYSTEMS

The variations in the design of roadside units are not considered major. In-vehicle equipment, however, may differ widely. It may consist of a tag (a small electronic device attached to the windshield of a car) or an IC card and a card reader, which are usually installed in the dashboard. Based on the design of the in-vehicle device, ETC systems can be classified as tag or IC card–based.

Tag-Based ETC Systems

In a tag-based system, the tag has memory, data processing, and communication capabilities, and it is also an RF device. On receiving a designated signal, it emits a radio signal of its own that is used for detection, identification, and location. A tag can be called a transponder. It can communicate without physical contact with a purpose-specific station over a distance ranging from a few millimeters up to several meters. The basic structure of a tag consists of several functional electronic circuits such as memory, control logic, RF modulation unit, and antenna. A tag can have its own power supply or operate without it.

Classification

According to its communication capability, a tag can be classified as read-only or read and write. A read-only tag can only be read by the roadside reader and is also referred to as a Type I transponder. A read and write tag (Type II transponder) can be read and also be written on by the reader. The information that is written can contain the tollgate identification, account balance, etc.

A tag can be classified as active, semiactive, or passive according to the source of power and its ability to generate its own RF signal or simply reflect the incoming signal. An active tag is always operational. It gets power from an internal battery or from the vehicle via a converter. Some active tags can receive a confirmation signal by the transceiver via the tag's RF unit, thus possessing a read and write capability.

A semiactive tag can also receive and transmit signals. However, it is not active in the absence of a transaction. It is activated only when it receives an interrogating signal from the reader's antenna.

In marked contrast to active and semiactive tags, passive tags have no power supply and thus can only be read after they collect enough power from the reader's RF signal to activate the electronics. They are primarily used in automatic vehicle identification (AVI) and early ETC systems.

Transmission and Modulation Methods

Whether a tag is active, semiactive, or passive, its transmission and modulation methods depend on the vendor. Intellitag's, Texas Instruments', SAAB's, and Amtech's tags, which are semiactive, use a "modulated backscatter" technology (*3*). The tag sends information back to the reader by changing or modulating the amount of RF energy reflected back to the reader antenna from a continuous-wave RF signal beamed from a reader. The RF energy is either allowed to continue traveling past it or is intercepted and "scattered" according to the tag's antenna pattern back to the reader antenna.

The operation of switching the "scattering" on and off can be done with very little cost in hardware and with very little electrical power. As a result, a tag can use so little energy that it can be powered with an internally integrated battery (similar to an electronic watch) or with power derived by rectifying the RF signal intercepted from the transceiver. Their efficiency, read and write capability, and low cost make these tags widely used in AVI and ETC.

Design and Data Storage

The information on the tag could be structured and stored in various ways, requiring different memory capabilities. The data storage capabilities usually differ among vendors. An example of a tag with read and write capabilities is given in Table 1. This particular tag, which happens to be the PREMID 3100, has a serial data package capability of 60 bytes (*2*). This data packet is divided into read and write portions. Table 1, Part *a* shows its read portion (bytes 0 to 23), which stores fixed data.

Table 1*b* shows that the write portion of the data (bytes 24 to 59) stores real-time information such as date, time, account value, and agency data. During each transaction, this portion of the memory must be rewritten to ensure that the toll amount is deducted from the account. In this example, the write portion contains sample data from a 1991 New York State Thruway Authority ETC field test.

Early tag designs called for data allocation to a specific physical portion of a tag's memory location. Current design calls for a "smart transponder," which is a microprocessor-based system with a flexible data structure (*4*).

Critical Tag-Based ETC Design Issues

Currently, there are two problems that plague tag-based ETC systems. The first problem is that products from different vendors use incompatible uplink and downlink hardware. The exceptions to this are the Amtech, Intellitag, and Texas Instruments systems, all of which use the same hardware. The second problem is that tags from different vendors have different data structure and storage capabilities. Either of these issues can lead to the problem of on-board to roadside unit incompatibility.

There are three ways to alleviate this problem. First, regional toll agencies can get together and select a common technology. This was the logic behind establishing interagency groups (IAGs) that

TABLE 1 Premid 3100 System Ample Serial Data Packet (*2*)

a. Read only portion

Information type	Location	Format	Content type
Tag type	Byte 0	W	Fixed ASCII char.
Application ID	Byte 1	T	Fixed ASCII
Group ID	Byte 2-3	01	Fixed code
Agency ID	Byte 4-5	01	Fixed code
Serial No.	Byte 6-11	nnnnn	Range 00001-000041
Checksum	Byte 12	C	Fixed ASCII char.
Vehicle type	Byte 13	1	Fixed
Vehicle profile	Byte 14	1	Fixed
Vehicle axis	Byte 15	4	Fixed
Revenue type	Byte 16	0-9	Fixed to 1
Agency data	Byte 17-21	NYSTA	Fixed ASCII string
Checksum	Byte 22-23	CS	Fixed

b. Write portion (for toll collection)

Information type	Location	Format	Content type
Plaza ID	Byte 26-27	01	01=Spring Valley 02=Tappan Zee
Lane ID	Byte 28-29	01	Fixed
Julian date	Byte 30-34	JUL04	Varies JAN01 to DEC31
Hour	Byte 35-36	hh	Varies 00 to 23
Minute	Byte 37-38	mm	Varies 00 to 59
Second	Byte 39-40	ss	Varies 00 to 59
Txn Number	Byte 41-44	nnnn	Increments with every successful transaction
Vehicle type	Byte 45	0-9	Revenue amount for debiting
Vehicle profile	Byte 46	1	Fixed
Vehicle axis	Byte 47	4	Fixed
Value	Byte 48-52	nnnnn	Reduced every transaction according to vehicle type stored in byte 45
Agency data	Byte 53-57	NYSTA	Fixed
Checksum	Byte 58-59	CS	Fixed

brought together various regional toll agencies to establish a common standard in the region. By ensuring that a selected technology will be used on all facilities, IAGs could increase ETC use and market penetration. The IAGs that are working out well include the following:

- The E-Z Pass, formed by toll agencies in the New York-New Jersey-Pennsylvania region, the operations of which account for some 37 percent of all U.S. toll transactions;
- The New England IAG;
- A California IAG, consisting of the Department of Transportation, Golden Gate Bridge, Highway and Transportation District, the Transportation Corridor Agency, and developers of four private toll roads; and
- The Greater New Orleans Expressway Authority and the Louisiana Department of Transportation and Development (*5*).

Second, different vendor processing software can be used at each tollgate, but this solution could prove impractical and prohibitively costly. Furthermore, a tag's fixed data structure makes it difficult to make modifications to adapt to future applications (e.g., traveler information service) that one of the regional agencies might offer.

The third and final solution is to develop tags that have flexible data structures so that they can operate in a multivendor environment. For example, Intellitag's tag (*6*) has an extended memory consisting of 20 data frames, each frame having 128 bits (a total of 2,560 bits). All but one of the frames can be programmed as fixed or variable according to a toll agency's data storage format. During each transaction, the tag's memory is read or written according to the "frame." This tag could be used with different toll agencies, as well as for other services (e.g., access control, parking management, etc.) (*7*).

IC Card–Based ETC Systems

The IC-based in-vehicle equipment consists of an IC card, a card reader (usually installed on the dashboard), and an RF link unit. An IC card, which incorporates a microprocessor, memory, and other electronic components, provides a means of storing information during each transaction. The RF link unit can be a tag mounted on the windshield or any other form of transponder that can establish a communication link between an IC card reader and the roadside equipment. This link can vary among different vendors from an ordinary frequency-modulated microwave signal to a spread-spectrum modulated signal.

System Description

The IC card consists of a microprocessing chip, memory, and input and output devices that are sealed with hard plastic or ceramic coating into a card. This design incorporates two innovative features. First, although in an ordinary IC (the reader can think of a personal computer as an analogy) the power line is linked directly to the IC's input pin, the IC card has no direct link with a card reader. Instead, an ultrathin printed circuit board with electronic components is "wire-bonded" to its surface. The card uses an "etched coil" to receive power and clock a signal from a card reader. When the card is inserted in the reader, the coil in the reader is coupled with the coil in the card, thus enabling the transfer of power and the clock signal between the reader and the card. Second, the data transfer is realized by using two pairs of "capacitor plates" in the card. The card has a custom IC to transfer data to and from the capacitor plates. The relative positions of a card and a card reader are very important, because the "etched coil" and "capacitor plates" of the two devices must be coupled for power and data transfer.

The reader has a data transfer circuit that uses the same custom IC that is used in the card to transfer data to and from the capacitor plates. This IC provides transistor-transistor-logic level signals that can be connected to a microprocessor serial port or RS232 drivers and receivers, which provide an interface between data terminal equipment and data communication equipment. Using this serial port, a card reader can be connected to any equipment such as a handheld reader, a personal computer, an automatic teller machine (ATM), a simple liquid crystal display (LCD), or a personal assistant system.

The card reader can also take on many different forms. It can be mounted inside a slotted plastic housing to form an insertion-type card reader or it can be mounted into the housing itself to form a surface-type card reader. The flexibility of interface also means that a card reader can be designed to be a freestanding device or it can be integrated into another device similar to the way a disk drive is mounted into a personal computer (*8*).

Special Security Device

Because an IC card contains a microcomputer, it is possible to employ many sophisticated security measures to protect the data integrity. For instance, the AT&T Smart Card has a personal identification number (PIN) protection. A special PIN is assigned for each directory and file access control security features. The security features may include many options, such as:

- One-time proof of user identity;
- User identity required every time a file is accessed;
- Card identity check before each transaction to prevent use of bogus cards; and
- User identity checking only at the IC card holder's request.

The above-mentioned file access control methods can be used in any combination, providing different degrees of data security (*9*). These features are especially desirable if an IC card is used in a multitoll operator region because they can be used to control access to each specific memory location.

IC Card Design Flexibility

An IC card has higher data storage capabilities than that of a typical tag [5 to 10 kilobytes (Kb) memory versus 2 to 3 Kb]. In addition, a change in the system's control function can be easily made by modifying its software at relatively low cost. This gives an IC card-based ETC two advantages over a tag based system. First, it can be modified easily to satisfy new standards. Second, if any portion of the memory is not functioning well, the problem can be corrected simply by redesigning the memory map of the card using the operating system command.

RECENT ETC APPLICATIONS

Because ETC can increase highway efficiency by reducing toll collection time and cost, many toll agencies in the United States and abroad are actively considering, testing, and implementing ETC technologies. Some of them are shown in Table 2, which is our updated 1992 Survey by the International Bridge, Tunnel, and Turnpike Association (*10*). A comprehensive review of the current application of United States and European electronic toll traffic management systems is given by Schuster (*5*).

Cost of ETC Systems

The costs of ETC systems (in 1993 dollars), obtained from the agencies that implemented them (e.g., Dallas North Tollway, Oklahoma Turnpike) are shown in Table 3 (*11*). It is indicated that early applications of ETC systems are very cost-effective (*5*). The Oklahoma Turnpike Authority reported $160,000 in savings per lane from replacing a single manual lane by the agency's PIKEPASS system.

ETC COMMUNICATION DESIGN ISSUES

Even the simplest ETC systems have rather complex communications needs. In-vehicle equipment must be identified and the relevant information must be transmitted between a vehicle and roadside unit. This information needs to be converted from a radio wave to a computer message, which must be processed through a computer system that will act on that message.

To guarantee a reliable communication data rate, operating frequencies and antenna selection must be considered. Reliable communication also depends on interoperability. Therefore a protocol

TABLE 2 Selected ETC Survey Results

Country, Agency and Facility	Lanes	Vendor	AVC	Enforcement
System under operation				
E-470 Public Highway Authority Colorado	4 dedicated 2 mixed	X-cyte	No	Video image
Dallas North Tollway Texas Turnpike Authority	4 dedicated 59 mixed	Amtech	Yes	Violation system
Oklahoma Turnpike Authority	56 dedicated 117 mixed	Amtech	Yes	Violation Surveillance
Crescent City Connection Louisiana Dept. of Transport.	3 dedicated 9 mixed	Amtech	Yes	None
Dartford River Crossing England	2 dedicated 6 mixed	SABB PREMID	No	Pre-classification Blacklisting
BRISA-Auto-Estradas de Portugal Portugal	8 dedicated	MICRO DESIGN	Yes	Video Retrieval System
Autostrade S.p.A Italy (IC card based ETC systems)	1800 dedicated	Autostrade S.p.A	Yes	Post-Payment Card
System under consideration				
E-Z Pass Group - New York - -- New Jersey --Pennsylvania (17 toll authorities)	varies between agencies	Finished the evaluation -- selected the AT&T-MARK IV	Yes	varies between agencies
Tobin Memorial Bridge Massachusetts Port Authority	N/A	Tested Amtech -- not decided	N/A	N/A
All roads North/South Illinois State Highway Authority	N/A	AT/Comm	N/A	N/A
Florida Turnpike Florida DOT	N/A	Finished testing - not decided	N/A	N/A
DRIVE Sweden (IC card based ETC systems)	N/A	Philips IC card	N/A	N/A
CGA/Gemplus HAMLET 2 French (IC card based ETC systems)	N/A	Premid and Schumberger IC card	N/A	N/A

Sources: International Bridge, Tunnel, and Turnpike Association, March 1992 (*10*),

TABLE 3 Equipment, Operating, and Maintenance Costs by Lane Type

Lane Type	Equipment Cost ($/lane)t	Operating and Maintenance Cost ($/lane)
Manual	58,500	141,900
Automatic	58,000	43,300
Manual/Automatic	107,500	111,000
Manual/AVI	72,700	146,100
Automatic/AVI	69,500	47,500
Manual/Automatic/AVI	121,300	115,200
AVI dedicated	15,400	4,200
Express AVI	15,400	4,200

Source: Pietrzyk, M. C. and E. A. Mierzejewski (*11*).

governing data format, error detection and correction method, and memory allotment is needed, just as for a computer communication network.

In an effort to resolve these issues, the Standards and Protocols Committee of ITS America published *Electronic Toll and Traffic Management (ETTM) User Requirements for Future National Interoperability* (Draft Version 2.0) (*12*). The standardization of different system design elements will not be easy, because the current systems are operating in various frequency ranges. Comparisons between the ITS America recommendations and vendors' data are shown in Table 4. For example, setting a certain frequency band for ETC communications (e.g., 5.8 GHz) will severely limit the competitive edge of vendors whose technology is outside the approved band.

European Experience

European promoters of ETC moved swiftly and set up an Europe-wide nonproprietary specification standard for ETC systems. This has been accomplished via a Vehicle Information and Transaction Aid (VITA) program. In late 1990, a VITA I document was developed by French, Italian, and Spanish toll agencies. It was revised in 1993, yielding the VITA II version. The document defined requirements for an open-protocol, two-way vehicle-roadside communication system with a high data rate, low bit-error rate, and low transaction error. The 5.8 GHz European Radio Communication Committee band was chosen for ETC communications. Additional VITA I and VITA II specifications can be found in Yacoubi (*13*).

TABLE 4 Comparison Between Draft 2.0 Recommendations and Vendors' Data

	Draft 2.0 recommendations	Intellitag	Amtech	Mark IV	SAAB Combitech
Frequency location	902-928 MHZ 2.45 GHZ, 5.8 GHZ	902-928 MHZ	850-950 MHZ 2400-2500 MHZ	902-928 MHZ	5.795-5.805 GHZ
Data rates	550 Kbps± 10%	300-600 Kbps	N/A	550 Kbps±10%	250 Kbps
Minimum capture rate	>99.95% or >99.00%	N/A	>99.9999%	N/A	99.99999%
Error rate	<0.00001%	N/A	(1-0.999999) %	N/A	0.0000001
RF characteristics					
Modulation (downlink)	ASK (Manchester)	ASK (Manchester)	ASK	ASK (Manchester)	ASK (Manchester)
Modulation (uplink) Active Backscatter	ASK (Manchester) AM subcarrier or FSK modulated at 600-1200 KHZ±10%	FSK modulated	FSK	ASK (Manchester)	FSK
Power density	<20μw/cm^2 (max)	N/A	100μw/cm^2 at surface	N/A	2.0W EIRP
Sensitivity	<1μw/cm^2 at toll booth when field strength<500 mv/m, tag should not respond	N/A	N/A	N/A	downlink >-43 dbm uplink>-100 dbm
Protocol					
data	HDLC, TDMA, binary	HDLC, TDMA, binary	N/A	TDMA, binary	HDLC, binary
error correcting	CRC-CCITT, Luhn code, ID check	CRC-CCITT, Luhn code, ID check	N/A	CRC-CCITT	N/A
Tags					
memory	PROM>256 bits, read/write>1Kbits	2560 bits total, flexible ROM and RAM allocation	N/A	N/A	N/A

TAG, IC CARD, OR COMBINED ETC SYSTEMS?

Currently, in the United States, tag-based ETC systems are widely used, whereas ETC IC card applications are nonexistent. However, the European experience of the Autostrade's AT&T Smart Card–based ETC system indicates that IC cards have enormous potential in ETC. This potential comes primarily from four unique features:

- The card's interface can be integrated into any other device such as a personal computer, ATM, or computer security device with little additional cost.
- The card can be attached to auxiliary on-board devices such as sensors for monitoring vehicle operation or display devices such as a CRT, LCD, or on-board computer.
- The card can be removed after use and is easy to carry.
- The communication link with other devices is not limited to RF (or microwave) communication.

It is this flexibility of the IC card and the potential of using it for a myriad of services that can make it the dominant medium for all electronic transactions. For example, the card can be used as a credit card, bank card, calling card, transit pass, parking card, and toll card, provided, of course, that these services have been equipped with an appropriate reader.

Europeans have already recognized the potential of IC cards. They have undertaken two major projects with the goal of designing a standardized ETC system with in-vehicle equipment based on an IC card. The Pricing and Monitoring Electronically for Automobiles (PAMELA) project was implemented to design and test a two-way microwave link within the Dedicated Road Infrastructure for Vehicle Safety in Europe (DRIVE 1) program. The Automatic Debiting and Electronic Payment project was implemented within the DRIVE 2 program to design, prototype, and field test a complete ETC system based on a microwave link developed in PAMELA. The system design calls for in-vehicle equipment built around the IC card. Figure 4 shows a schematic diagram of the in-vehicle equipment (*13*).

The French Toll Road Operators Association (USAP) should be given credit for initiating an international call for awarding a contract to build a French standard system for ETC. The USAP developed strict nonproprietary specifications, similar to those listed in VITA. In 1992, two consortia (one was led by CSEE Péage and included GEA and SAAB-SCANIA, and the other was led by CEG-ELEC-CGA and included GEM+), were awarded contracts to build the prototype systems, called télépéage intersociété. The prototype systems are currently undergoing indoor and field hardware and functional testing. It is expected that the selected system will be available in 1995 (*13*).

SECURITY AND LEGAL ISSUES

Clearly, ETC services may yield tremendous benefits to toll agencies and users. These technologies, however, monitor and control vehicle operations and trajectories and may elicit images of "Big Brother" watching. More to the point, those participating in the ETC program need to know whether information gathered by an ETC system may legally be used against them. The resolution of these issues will have an impact on market penetration, because people do not tend to participate in an activity in which they are being monitored.

Furthermore, two issues need to be distinguished: security and privacy. Security deals with protecting the integrity of the data transaction. For this purpose, the systems use various sophisticated techniques to prevent unauthorized users from gaining access to the authority and client information. These techniques vary from sophisticated data encryption techniques to password checking. For example, the actual user (tag) identity is scrambled and carried through the system as an unintelligible text.

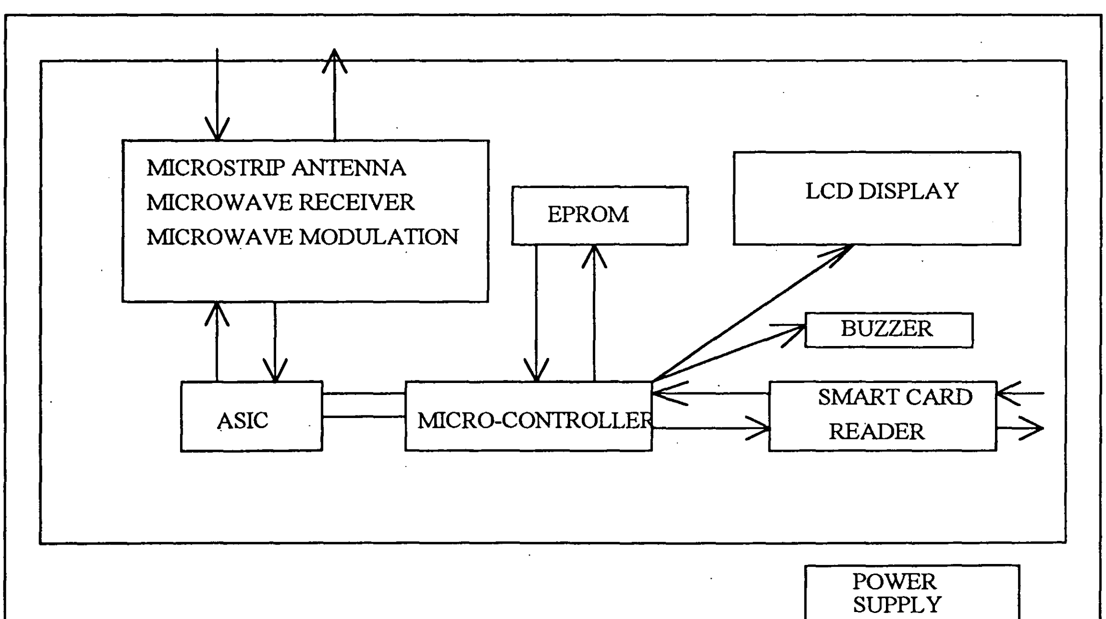

FIGURE 4 Schematic diagram of the in-vehicle equipment (*13*).

Assuming that the transaction has not been compromised, however, the question arises about whether a record of the transaction resides within the toll authority's files and whether it can be unscrambled and used to expose the user to potential legal liability.

In the read-only tag-based ETC system, the central data base stores all information concerning users' identification, account numbers, and account balances. The scrambled data communication records are also stored there. This stored information can be used to trace the movement of a particular vehicle. For example, law enforcement agencies may ask courts to order toll authorities to release data on a particular user's travel route, time, etc. This procedure is similar to the one in which a court asks a telephone company to provide detailed records on all calls, including the time of day for local calls, which usually do not appear on typical phone bills.

Introducing technology that records all transactions on a user device can alleviate this problem. For example, if one uses the read and write technology with a tag or an IC card as electronic money stored in the tag or card memory, the information resides with the user. Once the transaction between the roadside reader (authority) and the user is completed and all information regarding travel is stored on a card or tag and the user has left the system, the authority could purge all information about the transaction from its records. This operating procedure can put the user in control somewhat. However, the courts could subpoena the tags or IC cards from users as well.

TEST PROTOCOLS

With more agencies moving toward procurement of ETC systems, a set of consistent procedures must be developed to evaluate the performance of the systems. ETC system testing should include static, functionality, and long-term tests.

Static or controlled tests are performed in a laboratory to check a system's communication range and speeds, ability to withstand interference, reliability under harsh weather conditions, and electronic component reliability. A detailed description of the test protocols is given by Spasovic et al. (*14*).

Functionality tests are focused on assessing the functionality of tags or IC cards and can be performed simultaneously with static tests. They include tests to verify whether transaction information is correctly recorded, and fraud or cheating tests to identify potential loopholes in the systems.

Long-term tests are designed to test operational reliability of the system in an actual toll collection setting. They require that a large number of vehicles pass through the tollgate.

It is imperative that an ETC system can deliver a high degree of accuracy regardless of the adversity or hostility of the operating environment. The recommendation in ITS America Draft 2.0 (*12*) defines this accuracy in terms of capture rate (percent of successful reading and decoding of a properly mounted tag's data message) and error rate (percent reading error of a tag's identification fields). To satisfy these requirements, an ETC system must have a capture rate larger than 99.95 percent and an error rate smaller than 0.00001 percent (1 in 100,000).

Sample Size Estimation

If p denotes the probability of a successful transaction (neither read nor write errors occur) and q the probability of failure (i.e., $1 - p$), then the probability of k successful transactions during n tests is obtained by the binomial distribution:

$$P(Y = k) = \binom{n}{k} p^k q^{n-k}$$

Using the maximum likelihood estimation method, an estimate for p is:

$$\hat{p} = \frac{Y}{n}$$

and the estimation error is:

$$P\left\{\left|\frac{Y}{n} - p\right| < d\right\} \geq 1 - \alpha$$

where

$1 - d$ = measurement accuracy and
$1 - \alpha$ = confidence level.

If it is necessary to have a data capture of 99.95 percent and a confidence level of x, then:

$d = 1 - 99.95$ percent $= 0.0005$ and

$\alpha = 1 - x$.

For the binomial distribution:

$$P\left\{\left|\frac{Y}{n} - p\right| < d\right\} = P\left\{-d\sqrt{\frac{n}{pq}} < \frac{Y - np}{\sqrt{npq}} < d\sqrt{\frac{n}{pq}}\right\}$$

According to the Central Limit Theorem, the above probability can be approximated by the normal distribution as:

$$\Phi\left(d\sqrt{\frac{n}{pq}}\right) - \Phi\left(-d\sqrt{\frac{n}{pq}}\right) = 2\Phi\left(d\sqrt{\frac{n}{pq}}\right) - 1 \qquad (p + q = 1)$$

From

$$\mathrm{F}\left(d\sqrt{\frac{n}{pq}}\right) = 1 - \frac{\mathrm{a}}{2}$$

the sample size is:

$$n = \left(\frac{z\frac{\alpha}{2}}{d}\right)^2 * p * q$$

The required sample size depends on the measurement accuracy, confidence level, and probability of success. For a given measurement accuracy of 0.0005 and a probability of success, $p = 0.9995$, the required sample size varies with confidence level. For a 0.9 confidence level, the sample size is 1,645; it increases to 7,679 for a 0.95 confidence level.

The sample size is much more sensitive to the measurement accuracy than it is to the confidence level. For example, if the measurement accuracy is reduced from 0.0005 to 0.00001, and leaving p = 0.9995, the sample size becomes 13.5 million for a 0.9 level of confidence and 19.2 million for a 0.95 level.

CONCLUSIONS

Several issues relating to ETC technologies have been presented. The potential of these technologies is enormous. In addition to benefits related to toll collection, these technologies are capable of providing added value because they can be used in many other transportation services such as traffic management and traveler information, as well as for nontransportation services such as access control, distribution of benefits, and so forth. The technologies, however, are not mature, and as such, they have not been thoroughly field tested. The proprietary nature of the devices and the large sample sizes required to validate claims of accuracy may force the transportation profession and the general public to wait a relatively long time for the best devices to rise and become industry leaders and reliable off-the-shelf items. Industry, public sector, and academic consortia formed for the testing of existing or future devices and technologies would speed up the evaluation process in realistic operational environments, while at the same time maintaining the confidentiality and safeguarding the proprietary nature of the technologies.

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