ELECTRONIC TOLL COLLECTION SYSTEMS

by

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SUMMARY

Toll facilities are created as a means of improving the existing highway infrastructure when public funds for the project cannot be allocated. These facilities serve as alternate routes for already congested routes for those willing to pay a toll for use of the facility.

Due to inefficient methods of collecting these tolls, however, a number of problems result. Congestion and long queues often form at the toll plazas due to the limited throughput of manual collection methods. These queues and stop and go traffic in turn increase fuel consumption and vehicular emissions. Manual toll collection methods are also very labor intensive and expensive to implement.

Advances in Automatic Vehicle Identification (AVI) systems in recent years have made Electronic Toll Collection (ETC) systems not only possible, but a very feasible method to eliminate the problems associated with manual toll collection methods.

There are a number of ETC systems currently on the market which use differing technology, but serve the same purpose of allowing tolls to be collected electronically and automatically requiring no action by the driver. These systems can be categorized as optical and infrared, inductive loop, radio frequency/microwave, surface acoustical wave and smart card systems.

Although there are various technologies available that institute AVI, common to all AVI systems are several basic elements: a vehicle mounted transponder (toll tag), a roadside reader and antenna array, a master computer system for processing and storage of data and an enforcement system.

There are a number of limitations associated with optical, inductive loop, and surface acoustical wave systems which make radio frequency based systems the ETC system of choice for most toll facilities today.

ETC offers toll authorities a more sophisticated means of collecting tolls while at the same time providing significant reductions in infrastructure, operating and maintenance costs. Throughput of ETC lanes is on the order of three to five times that of lanes utilizing manual and automatic coin machine methods.

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INTRODUCTION

There are currently over 160 bridges and tunnels and 98 roads being operated as toll facilities in the United States (1). Toll roads can be divided into two categories, either ticket systems or mainline/ramp barrier systems. In a ticket system, a ticket is received upon entry and returned with payment when leaving. In a mainline/ramp barrier system, payment is rendered when crossing each barrier, located approximately every 12 miles on the mainline and on either exit or entrance ramps between mainline barriers.

The first and most common form of toll collection is manual collection of currency by toll booth attendants. Various other manual strategies have been implemented in an effort to increase throughput and user convenience. These strategies include the use of automatic coin machines to replace attendants and the use of coupons and tokens to replace currency, limiting receipts to certain lanes only and provide exact change lanes.

Problems with Traditional Toll Collection Methods

Limited Throughput

The two traditional forms of toll collection are by either an attendant in a booth or an automatic coin machine. These methods are extremely inefficient due to the requirement of the motorist to stop when rendering payment. Toll booth attendants can process approximately 350 vehicles per hour while automatic coin machines can process approximately 500 vehicles per hour (2). To ensure that the capacity of a facility is not constricted by the capacity of the toll plaza, five to six toll lanes would be required for each lane of traffic. This is typically not feasible and two or three toll lanes per lane of traffic are usually provided instead. The result is the formation of queues and subsequent delay to the motorist.

High Infrastructure Costs

The result of requiring a large number of toll lanes is high infrastructure costs. In addition to the costs associated with acquiring right-of-way, providing expansive paved surfaces and constructing the toll plaza there are the lane equipment costs. The cost to install a manual toll booth is approximately $58,500 per lane and the cost of the automatic coin machine is approximately $58,000 per lane (3). When considering the large numbers of toll lanes provided at toll plazas and the fact that most toll authorities provide both manual toll booths and automatic coin machines on at least a percentage of the lanes to maintain operational flexibility, it is easy to see the extensive infrastructure investments required with the use of these toll collection methods.

High Operating and Maintenance Costs

In addition to the high infrastructure costs, these collection methods incur extensive operation and maintenance costs. An automatic coin machine has an associated operation and maintenance cost of approximately $43,300 per lane per year while a manually operated toll booth has an associated operation and maintenance cost of approximately $141,900 per lane per year (3).

Increased Accident Potential

Because vehicles are required to stop at toll plazas, high speed differentials exist between vehicles as speeds are reduced from 55 mph to a stop. In addition, weaving maneuvers upstream of the toll plaza are common as a limited number of lanes fan out to a much greater number of toll lanes and drivers seek exact change lanes, lanes which provide receipts or the lane with the shortest queue. The reverse is also true downstream of the toll plaza as the large number of lanes are reduced to a few lanes. The combination of high speed differentials and weaving maneuvers contribute to an increased accident potential.

Increased Emissions

An issue receiving greater attention recently is that of automotive emissions. As will be graphically shown later in this paper, vehicle emissions are much higher at idling and low speeds than normal facility speeds. Thus, by requiring vehicles to stop at toll plazas and idle in stop and go queues, emissions are greatly increased over those produced on a normal section of the facility.

Electronic Toll Collection

The problems associated with traditional toll collection methods have created a need for a more advanced and sophisticated method of collecting tolls. Electronic toll collection (ETC) systems fill that need. While there are a variety of ETC technologies that have been developed based on various automatic vehicle identification (AVI) technologies, they all share the common principle of being able to automatically identify and assess tolls to a user's account while requiring no action by the driver.

ETC systems have been implemented on a number of facilities in recent years and are being planned for new facilities. A list of some facilities using and planning for ETC can be seen in Table 1.

Objectives

The three main objectives of this research were to: 1) identify and discuss the various ETC systems available to toll agencies, 2) compare the advantages and limitations of each type of system and 3) discuss related issues that need to be considered by toll agencies contemplating the implementation of ETC systems such as equipment, operating and maintenance costs, user privacy and health safety, toll plaza design, payment systems, standardization and public perception and preferences.

Table 1. Examples of U.S. Electronic Toll Facilities.

Toll Roads	Tunnels and Bridges
Dallas North Tollway	Coronado Bridge
Dulles Toll Road	Greater New Orleans Bridge
New York Thruway	Grosse Ile Bridge
Turner Turnpike	Tobin Memorial Bridge
Will Rogers Turnpike	Verrazano Narrows Bridge
H.E. Bailey Turnpike	Pinellas Bayway Bridges
Indian Nation Turnpike	Sanibel Causeway
Muskogee Turnpike	Cape Coral Bridge
Cimarron Turnpike	Walt Whitman Bridge
John Kilpatrick Turnpike	Benjamin Franklin Bridge
Cherokee Turnpike	Betsy Ross Bridge
Chickasaw Turnpike	Commodore Barry Bridge
Creek Turnpike	Thomas J. Hatem Memorial Bridge
Denver E-470	Goethals Bridge
Sam Houston Tollway	Lincoln Tunnel
Hardy Toll Road	Baltimore Harbor Tunnel
Orlando/Orange County Expressway	Tappan Zee Bridge
Everett Turnpike	

Planned Facilities
Georgia State Route 400
Interstate 355 Chicago
Two Boston Tunnels
California State Route 91
Three Orange County toll roads
Atlanta Tollway
Kansas Turnpike System
Massachusetts Turnpike Authority
Florida Turnpike System
San Francisco-Oakland Bay Bridge
Carquinez Bridge
Regional system for New York, New Jersey and Pennsylvania

Scope

This report is a summary of the technologies which have been developed for automatic vehicle identification and can be used for electronic toll collection. The emphasis is on general system characteristics of each technology rather than a survey of individual vendor systems.

Method of Study

To accomplish the objectives of this paper, a great deal of information was obtained from the International Bridge, Tunnel and Turnpike Association (IBTTA), the University of South Florida College of Engineering, several manufacturer's of ETC equipment used in the United States (Amtech Corporation, AT/Comm, Hughes, Vapor Canada, Mark IV Industries Limited and Texas Instruments) and articles from various technical journals.

Organization of Report

The report body is organized into three major sections: ETC system components, ETC technologies and issues associated with ETC implementation. The major conclusions of this study are summarized in the findings section. Specific recommendations regarding the use of ETC systems and associated issues are presented in the final section.

ETC SYSTEM COMPONENTS

Although there are various technologies available that institute AVI, common to all AVI systems are several basic elements as seen in Figure 1: a vehicle mounted transponder (toll tag), a roadside reader and antenna array, a central computer system for processing and storing account data and an enforcement and detection system. The AVI system in general works as follows.

The RCU broadcasts an interrogation signal from its antenna. When a vehicle comes within range of the signal, the transponder broadcasts its identification code back to the RCU which decodes and validates the identification code. This information is then transferred to the central computer system which debits the account and maintains all transaction records. The transponder and reader/antenna technology utilized in a system are independent of the computer system used for management and accounting.

Transponder

Transponders can be classified according to power requirements and the level of programmability. These classifications are active, passive, semi-active, Type I, Type II and Type III.

Active

An active tag requires a power source, either in the form of an internal battery or connection to the vehicle's power supply. In an active tag system, the RCU's interrogation signal activates the tag. The tag responds by generating and broadcasting, from an internal transmitter, its own signal which contains the data stored in the tag. The active tag has a greater operating range and is more reliable than the passive tag due to its stronger signal, but requires more complicated circuitry and has a greater probability of experiencing lane to lane interference due to the stronger signal. Active tags with internal power supplies have life expectancies between 7 to 10 years (5).

Passive

In a passive tag system, the tag requires no internal or external power supply. Instead, the tag circuitry is powered by the interrogation signal itself. The signal transmitted by the RCU is merely altered (modulated) and reflected back to the reader. The passive tag is less complex than the active tag and has a lower probability of lane to lane interference due to the lower return signal strength. However, as a result of the weaker signal, the passive tag has a shorter operating range and is more susceptible to electrical interference. Passive tags, due to their simple circuitry have life expectancies of approximately 40 years (6).

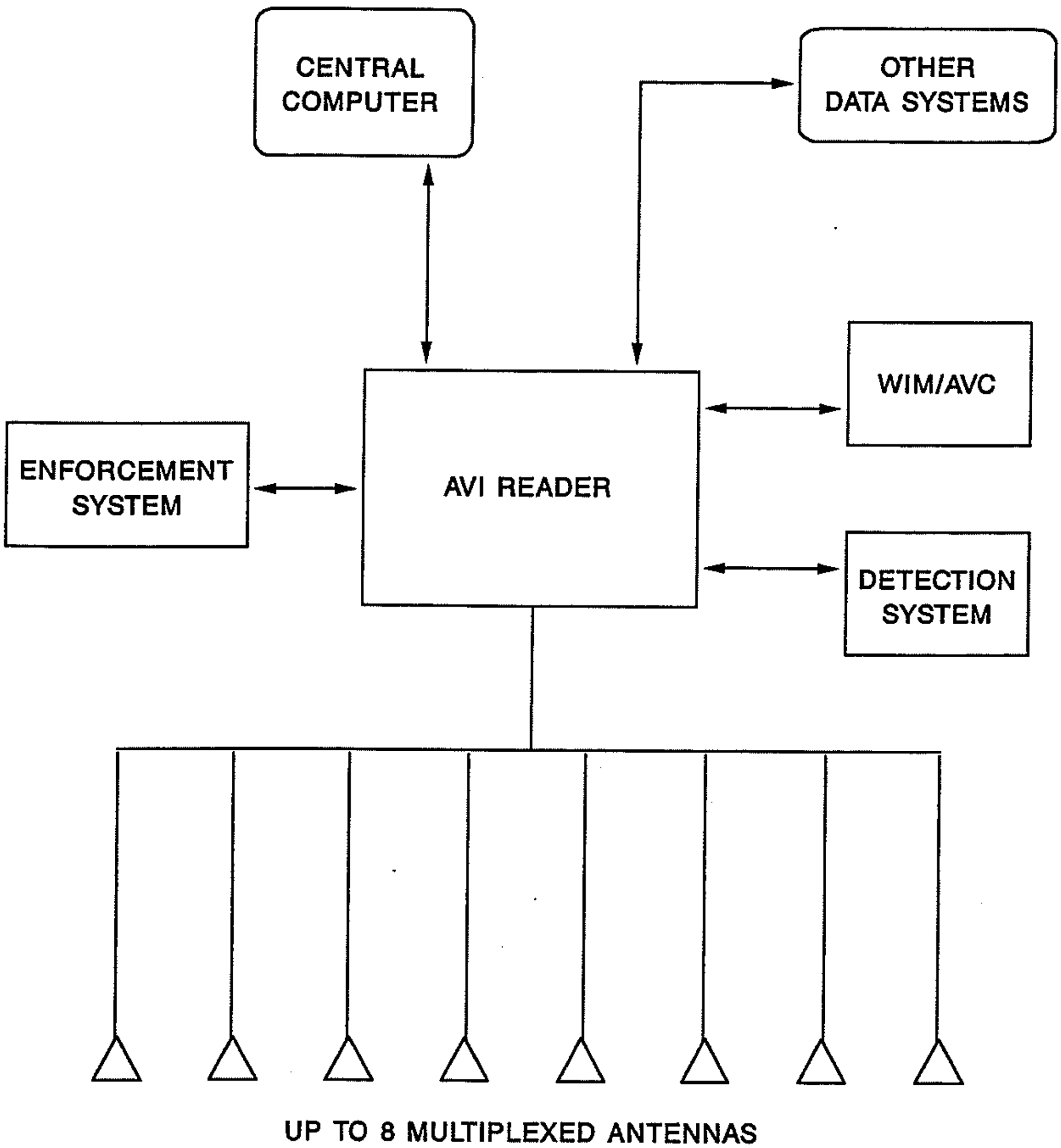


Figure 1. ETC System Components (4).

Semi-Active

Semi-active tags attempt to overcome the shortfalls of the passive tag by incorporating an internal power supply. The tag still operates under the same principles as a passive tag, but utilizes the internal battery to boost the reflected signal, which increases the reading range. As active tags, semi-active tags have a life expectancy of approximately 7 to 10 years (5).

Type I

Type I tags, also know as read-only tags, contain fixed data such as vehicle or tag identification number and vehicle classification code. The data are either programmed at the factory or by the agency issuing the tag and cannot be reprogrammed without returning the tag to the factory or tag center. Most read-only tags contain a 64 bit memory which is equivalent to a 20 digit alphanumeric code (4). Read-only tags communicate this fixed data to the RCU where identification and validation occurs.

In a barrier ETC system the tag is identified at a toll station and the toll deducted from the account. In a ticket system, the entrance location, time and date are recorded with the tag identification code in the RCU and transmitted to the central computer system. Upon exiting the ticket system the RCU compares the exit data with entrance data and calculates the fare which is debited from the account.

Type II

Type II tags, also known as read/write tags, have the same fixed data memory as the Type I tag, but also incorporate an additional memory field, of approximately the same size as the fixed memory field, which can be reprogrammed or written to remotely from the reader. These tags contain enough extra memory to carry information such as transaction location, lane number, time, date and account balance.

Thus, in a ticket toll system, the entrance data, location, time and date, can be written onto the tag by the RCU at the entrance point, read and compared to the exit data to determine the appropriate toll.

The sequence of events in a read/write communication process with the RCU is as follows: tag enters read range, RCU reads tag identification number from fixed data memory, RCU determines message to be written to tag, RCU reads tag until signal is strong enough for write transaction, RCU sends write message with tag identification number to the tag, properly addressed tag accepts write message and RCU reads back data in both fixed and programmable memory to verify tag identification number and write message. This entire process is accomplished in under a tenth of a second. (7).

Type III

Type III tags, also known as smart cards, are used in conjunction with a smart card reader and transponder. This is the newest of the three tag technologies and is not currently used in the United States. Smart tags have extended memory and are capable of full two-way communications with the roadside.

Roadside Communication Unit (RCU)

The RCU is made up of one or more antennas, a radio-frequency transmitter receiver, a microprocessor and software and a data buffer. In some systems, a single reader can be multiplexed with up to eight antennas which is usually enough to handle the ETC lanes in both directions.

The RCU generates and broadcasts an interrogation signal and receives, decodes and validates the return signal from the transponder. Transaction records can either be sent directly to the central computer system or stored in the data buffer and downloaded at certain time intervals.

In an active system, the RCU interrogation signal serves only to activate the tag to broadcast its signal. Therefore, in an active system only brief pulses need to be broadcasted.

In a passive system, the RCU interrogation signal must power the tag circuitry and thus must be a continuous signal. This type of a system results in a much higher power density field than the pulsed system.

Central Computer System

The central computer system downloads transactions from the RCU to maintain accounts and ensure that funds were collected and distributed properly. All RCUs in the toll system are linked to the central computer system by modems. Transaction data can be downloaded in real time or periodically.

Enforcement System

A necessary component of any ETC system is an automatic enforcement system to deter violations and to detect those that do occur. The enforcement system not only detects and identifies vehicles without transponders, but also vehicles with malfunctioning transponders, reported lost or stolen transponders or users whose account balance is too low to pay for the toll.

Enforcement systems consist of a photographic system and loop detectors for each lane. As a vehicle approaches a toll facility its presence is registered through an entrance inductive loop in the pavement. If no response from the interrogation signal is detected by the reader by the time the vehicle reaches the exit loop detector, a violation is registered and a still photographic or video system is activated to photograph the violators' license plate. Other information such as date, time and lane number to document when and where the violation took place can be superimposed on the picture. The owner is then identified and can be mailed a moving violation ticket for toll evasion.

Most states where AVI is being used have passed statutory laws enabling violators to be legally identified and fined based on videotape evidence. Before these laws were passed most states required an officer to witness the violation before a citation could be issued.

ETC TECHNOLOGIES

Various AVI technologies have been developed and implemented in ETC systems around the world. These technologies can be classified as optical and infra-red systems, inductive loop systems, radio frequency and microwave systems, surface acoustic wave systems and smart card systems. It should be noted that the technologies utilized by some of the above systems are not completely exclusive of each other, but that this classification scheme is used to emphasize the differences of the systems. A relative comparison of these technologies is summarized in Table 2.

Optical and Infra-red Systems

Optical systems were originally developed in the early 1960s for the American Association of Railroads for the purpose of tracking boxcars. Infrared systems operate similarly to the optical systems, however have slightly more penetrating ability. There are two main types of optical systems.

The first type of optical system utilizes a simple bar code sticker as the vehicle tag, which is placed on the outside of the vehicle such as on a side window. An optical or infrared laser continuously scans over a specific area where the tag is expected to be. As the vehicle passes the scanner, the reflected signal, representing the unique lines of the coded label is collected and processed to identify the vehicle. This process takes approximately a quarter of a second (9).

Optical and Infrared scanners operate at frequencies between 10^5 and 10^9 MHz. Reading can occur at speeds of up to 45 mph depending on the size of the bar code but only up to a distance of approximately 8.5 feet (10).

The second type of optical system utilizes an image processing system. As a vehicle passes the toll booth, a video camera records an image of the back of the vehicle. The image is digitized and processed to extract the license plate number.

Advantages

The advantages of Bar Code Optical Systems are:

1) inexpensive tags (less than $2),
2) low potential for lane to lane interference and
3) faster and more reliable than license plate reading systems.

Table 2. Relative Comparison of ETC Technologies (8).

Issues/Technologies	Bar Code	Inductive Loop	RF	SAW
Reliability	low	high	high	medium
Resistance to Duplication	low	medium	medium	high
Potential for Multiple Reads	low	low	high	high
Resistance to Interference	high	high	low	low
Tolerance to Environment	low	medium	high	high
Simplicity of Tag	high	low	low	medium
Health Safety	high	high	high	high

The advantages of License Plate Reading Optical Systems are:

1. no special tag is needed,
2. license plate duplication is not likely, and
3. no chance of lane to lane interference.

Limitations

The limitations of Bar Code Optical System are:

1. performance adversely affected by rain, fog and snow and dirty tags,
2. limited operating range (less than 10'),
3. easier tag duplication than other AVI systems, and
4. sensitivity to tag misalignment.

The limitations of License Plate Reading Optical Systems are:

1. expensive and complex image processing equipment,
2. slow processing time (approximately 1 second) allowing for only a single read as opposed to multiple reads which reduce error rates, and
3. performance adversely affected by rain, fog and snow and dirty license plates.

Examples

Bar code reading optical/infrared ETC systems have been used on the Sanibel Causeway and Cape Coral Bridge in Lee County, Florida, the city of Treasure Island, the Thomas J. Hatem Memorial Bridge in Perryville, Maryland, the Reynolds Channel Bridge near Brooklyn and four bridges in the Philadelphia area, the Walt Whitman Bridge, the Benjamin Franklin Bridge, the Betsy Ross Bridge and the Commodore Barry Bridge.

Image processing of license plates for ETC has been used on several French toll roads, but have not achieved low enough error rates for widespread implementation.

Manufacturers

Manufacturers of optical technology include LazarData, Automatic Toll Systems, Inc. and AMSKAN Identification Electronics.

Inductive Loop Systems

Inductive loop ETC systems utilize an antenna loop, similar to a loop detector, imbedded in the pavement to communicate with the vehicle's transponder as the vehicle passes over the loop. The return signal from the transponder is returned to the antenna loop and transmitted to the computer for data processing. In this system, the transponder is usually affixed underneath the vehicle or to the license plate.

Inductive loop systems operate at low frequencies from 50 to 500 KHz which results in slower transmission rates than other AVI systems. However, transmission is fast enough to allow multiple reads and can be used with vehicle speed up to 100 mph (9).

Inductive loop systems can be used in conjunction with passive, semi-active and active transponders although active systems are most common.

Advantages

The advantages of inductive loop systems are:

1. greater reliability due to proximity of tag to antenna,
2. very low potential for electrical interference, and
3. low potential for lane to lane interference.

Limitations

The limitations of inductive loop systems are:

1. performance adversely affected by steel-reinforcement in pavement,
2. lower data transmission rates because of low frequency communication and
3. more difficult tag instillation.

Examples

Inductive loop ETC systems have been used in Hong Kong.

Manufacturers

Manufacturers of inductive loop technology include Plessy, Eureka Systems Inc., Vapor Canada and EMX Corporation.

Radio Frequency (RF) and Microwave Systems

This technology, while relatively new to the toll collection industry has been used in a number of applications including facility access control, monitoring of elderly patients in hospitals, tracking of pallets, containers or even animals, fleet management, automatic weighbridges, automatic fuel dispensing and refuse container identification (11).

As with inductive loop systems, RF systems can be used with active, passive or semi-active tags. However, by operating at higher frequencies than inductive loop systems, usually at 915 MHz, RF systems are able to transmit greater amounts of data at higher speeds. The identification process of an RF system is accomplished in less than a tenth of a second (7).

With RF systems, vehicle tags are usually mounted on the front windshield and communicate with the roadside reader via antennas mounted overhead. RF systems have a much greater range than previously mentioned systems, up to 235 feet at speeds of up to 180 mph (9).

Advantages

The advantages of active RF systems are:

1. greater operating range,
2. greater reliability due to stronger return signal, and
3. lower chance of electrical interference.

The advantages of passive RF systems are:

1. no required power supply,
2. less complex tag circuitry, and
3. lower chance of lane to lane interference.

Limitations

The limitations of active RF systems are:

1. greater complexity of tag circuitry and lower life expectancies than passive tags,
2. greater probability of lane to lane interference due to stronger signal, and
3. requirement for power supply.

The limitations of passive RF systems are:

1. lower reliability than active system,
2. greater chance of electrical interference due to lower signal levels,
3. shorter operating range, and
4. higher overall level of radiation from RCU.

Examples

RF/Microwave systems are by far the most common ETC system in and include the Dallas North Tollway, Lincoln Tunnel, Greater New Orleans Bridge, Denver E-470, Hardy Toll Road, Sam Houston Tollway, Dulles Toll Road and a system of ten turnpikes in Oklahoma.

Manufacturers

Manufacturers of RF/Microwave technology include Amtech Corporation, Hughes, Philips, Texas Instruments, AT/Comm, Vapor Canada and AMSKAN Identification Electronics.

Surface Acoustical Wave (SAW) Systems

Surface Acoustical Wave systems operate much the same as RF/microwave systems but differ in transponder technology. The SAW transponder is a passive, non-reprogrammable tag. As the interrogation signal is received by the tag, an internal lithium crystal converts the signal into acoustical waves which travel along the crystal's surface. Etched metal taps on the crystal's surface are used to reflect a specific wave pattern which is in turn reflected back to the AVI reader to uniquely identify the vehicle.

As this is a passive system with low powered transmissions, operation range is limited to a distance of up to 15' at vehicle speeds of up to 55 mph (9).

Advantages

The advantages of SAW systems are:

1. simpler tag circuitry than other AVI tags,
2. less expensive manufacturing costs than other AVI tags,
3. practically impossible to duplicate tag, and
4. low potential for lane to lane interference.

Limitations

The limitations of SAW systems are:

1. limited operating range, and
2. read-only capability.

Examples

Surface Acoustical Wave systems have been used at the Coronado Bridge in San Diego, the Grosse Ile Bridge near Detroit and Oslo, Norway.

Manufacturers

Manufacturer of SAW technology include 3M Corporation, X-CYTE, Inc., Science Applications International Corporation (SAIC), Micro Design and Siemens.

Smart Card Systems

Smart card technology is the newest of the AVI technologies being used and is based on a two-way communication via microwave transmission between the roadside reader and a "smart" on-board unit. The on-board unit is composed of a smart card, a smart card reader and a transponder. In addition to the integrated circuits found in RF tags, smart transponders contain a microprocessor which can perform both read and write functions.

In a smart card system the on-board unit acts as an electronic purse, similar to stored value cards, in which the user's account information and electronic funds are held as opposed to in a central computer system. As the vehicle passes a toll station, a signal is sent to the transponder which debits the smart card according to instructions from the roadside reader.

Refilling stations in the form of an ATM type of machine would be provided at various locations where the user can add additional value to the card. Smart card memory is sufficient to hold the last 400 transactions which can be displayed in toll plazas in case of a dispute or can be printed out for a personal record (12).

As the value is stored in the tag itself, this may make theft of the tag a potential problem. If an RF-based tag is stolen, it becomes worthless once reported, however in the case of smart cards, they are untraceable and useable by anyone. A possible solution to this problem may be to require the entry of a P.I.N. number as is used for ATM withdrawals.

In Europe, AVI systems operate at the 2450 MHz frequency which allows for faster transmission rates. One smart card system developed in Europe, PREMID 3100, can operate at a range of up to 33' and vehicle speeds of over 200 mph (13).

Advantages

The advantages of smart card systems are:

1. elimination of centralized computer system to handle individual user accounts,
2. assured user privacy,
3. toll charges seen on in-vehicle display, and
4. traffic and/or safety advisories via radio beacon seen on in-vehicle display.

Limitations

The limitations of smart card systems are:

1. higher costs for on-board system than other AVI transponders,
2. multi-lane communication problems, and
3. theft potential.

Examples

Smart card technology use up to this point has mainly been limited to Europe.

Manufacturers

Manufacturers of smart card technology include General Motors Corporation, AT&T, Vapor Canada and Philips.

ISSUES ASSOCIATED WITH ETC IMPLEMENTATION

There are a variety of issues that should be considered when planning to implement an ETC system. These issues include the associated costs, privacy and health safety of the user, toll plaza design, payment systems, emissions, standardization and public perception.

Costs

Perhaps the most important issue for toll authorities is the cost of ETC implementation and operating and maintenance costs. As well as offering benefits such as the elimination of delay at toll facilities due to toll collection and reduction of vehicular emissions and fuel consumption, ETC systems offer significant savings in equipment, operating and maintenance costs.

For the following figures, average operating and maintenance costs and lane equipment costs for conventional toll collection systems were provided by the Office of Toll Operations-Florida Department of Transportation. Average operating and maintenance costs and lane equipment costs for ETC systems are based on costs provided by the Oklahoma Turnpike Authority, Denver E-470 Tollway, Dulles Fastoll, Crescent City Connection and Dallas North Tollway.

Equipment Costs

A comparison of per lane equipment costs for conventional toll collection systems and ETC systems can be seen in Figure 2. ETC equipment provides a savings of over $42,000 per lane compared to manual and automatic coin machine equipment costs.

Operating and Maintenance Costs

A comparison of per lane average annual operating and maintenance costs for conventional toll collection systems and ETC systems can be seen in Figure 3. With an annual savings of $39,100 compared to automatic coin machines and an annual savings of $137,700 compared to manual toll booths the cost-effectiveness of ETC systems is clear.

Privacy

While the idea that vehicle location and times are identified and recorded by ETC systems may conjure up ideas of "Big Brother" monitoring people's movement to some, the significance of this fact tends to be exaggerated. These records are no different from the records kept by various organizations. Telephone companies keep itemized records of phone calls, banks record checks on microfilm and compile lists of credit card purchases and even video stores keep a history of all the tapes rented by a customer.

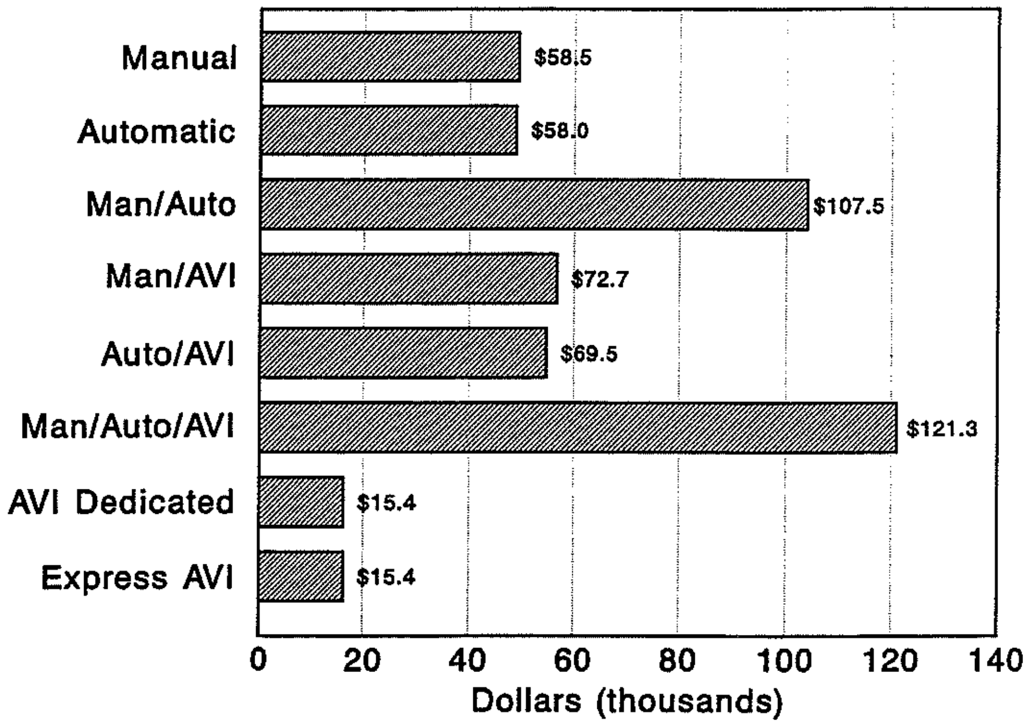


Figure 2. Average Lane Equipment Costs (3).

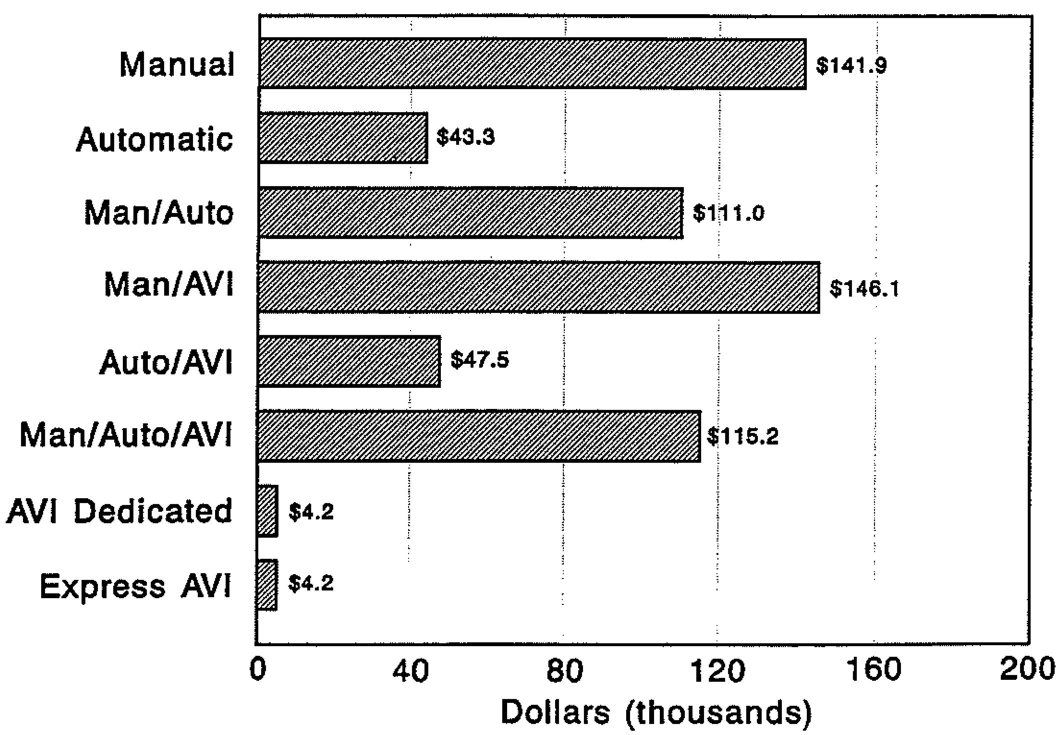


Figure 3. Average Annual Operating and Maintenance Costs (3).

For those with heightened concerns about privacy, toll authorities, as does the Dallas North Tollway system, can provide the payment option of maintaining a special anonymous prepaid cash account similar to a Swiss bank account. Thus, there is no connection between the account number transmitted in the toll collection process and the user's identity.

Health Safety

With increased public awareness of potential health risks and fears of effects from electromagnetic radiation, this issue should be addressed. The effects of electromagnetic radiation can be categorized as ionization, heating effects and biological effects. The first two effects are of no consequence to AVI systems as ionization can only occur at very high frequencies such as x-rays and heating effects can only occur for very high power densities.

Biological effects are a function of both the frequency and power density of the radiation, of which power density is the most critical factor. The power and frequency levels of the various AVI systems as well as some other common systems can be seen in Table 3.

If the power output of the AVI system is assumed to be 500 mW, the maximum power density at a distance of one meter from the antenna can be calculated from standard antenna theory to be approximately 40 $\mu W/cm^2$ (8). This value is well below even the most conservative of the recognized power density standards seen in Table 4. To put power density associated with AVI systems in perspective, a cellular telephone transmitting four watts at a distance of five centimeters has an associated power density of 6,400 $\mu W/cm^2$ which is 160 times that of the AVI system (8).

It should also be noted that most AVI systems operate at power levels well below the assumed 500 mW, the AVI user will be more than one meter from the antenna and that exposure time will be less than one second. Thus, there should be no doubt that AVI systems are safe for its users.

Toll Plaza Design

The implementation of ETC lanes at toll facilities can be designed as either dedicated or mixed use.

Mixed Use Lanes

Mixed use lanes incorporate ETC equipment in addition to manual toll collection systems and allow use by all facility users. As the benefit to the ETC user is minimal in this arrangement, on the order of five seconds, there would be little incentive to pay tolls electronically. The main reason for incorporating ETC equipment in mixed flow lanes in the past has been due to ETC market uncertainty by toll agencies which are reluctant to sacrifice a lane for exclusive ETC use and negatively impact the remaining lanes.

Table 3. Power and Frequency Level Comparisons (9).

	Power (milliwatts)	Frequency (megahertz)
AVI Systems		
Optical/Infrared	2-3	10^5-10^9
RF/Microwave	40-50	100-2000
Surface Acoustical Wave	30	100-2000
Inductive Loop	100-1000	.05-.5
Other Common Systems		
CB Radio	4000	27
Microwave Oven	10^5-10^6	1000-3000
"Ham" Radio	10^3-10^6	1-1000
Cellular Telephone	500-5000	200-900
Radio Control	500-1000	10-1000
AM Radio	500-1000	.55-1.6
FM Radio	500-1000	88-108
Television	10^7-10^8	50-500

Table 4. Power Density Standards (8).

American National Standards Institute	3,000 $\mu W/cm^2$
International Electrotechnical Commission	10,000 $\mu W/cm^2$
National Radiological Protection Board	1,200 $\mu W/cm^2$
Occupational Safety & Health Agency	10,000 $\mu W/cm^2$
Environmental Protection Agency (proposed)	300 $\mu W/cm^2$
Soviet Occupational Standard	200 $\mu W/cm^2$

Dedicated Lanes

There are two types of dedicated lanes: low speed barrier lanes and high speed separated lanes. The design of low-speed dedicated barrier lanes is most applicable in the case of retrofitting an existing barrier toll plaza with ETC equipment. In this case, vehicles can only be allowed to travel through dedicated lanes at the toll plaza at low speeds of 30 to 35 mph due to a variety of safety factors.

The first limitation is lane width at the barrier. As these lanes were designed for stop and go traffic, they are not sufficiently wide to safely permit high speed travel. The second limitation is proximity to manual toll collection lanes. The potential for high speed differentials between adjacent lanes is a major contributing factor to traffic accidents. This potential would exist both as vehicles approach the toll plaza and again as vehicles starting from a stop try to merge with vehicles traveling at much higher speeds. This arrangement also presents a safety hazard to toll attendants needing to cross toll lanes to get to their assigned booth. A diagram of an ETC dedicated lane within a barrier toll plaza can be seen in Figure 4. An example of this type of dedicated lane is the Dallas North Tollway which can be seen in Figure 5.

The second type of dedicated lane is most common in newly constructed toll facilities. To circumvent the safety hazards associated with barrier dedicated lanes, the dedicated lanes can be separated from the manual toll collection lanes altogether. These lanes are often called express lanes because of their high-speed nature. By diverging and merging dedicated ETC lanes from manual toll collection lanes approximately one-half mile upstream and downstream of the toll plaza, high speed travel on ETC lanes can safely be achieved. A diagram of the toll plaza design to be used for the new Orange County toll roads in California which incorporate dedicated lanes separated from the manual toll collection lanes can be seen in Figure 6. An example already in use is the John Kilpatrick Turnpike in Oklahoma which can be seen in Figure 7.

A comparison of the various capacities of different toll collection systems is provided in Figure 8. As seen in Figure 8, a marginal increase in capacity is observed when ETC systems are implemented in conjunction with manual toll collection systems. However, it is the use of dedicated and express ETC lanes which offer significant improvements in capacity.

Payment Systems

Payment options available to toll authorities include payment by credit card, electronic funds transfer, check and cash either in a pre-payment or post-payment account. A survey of several ETC system operators regarding payment systems available to the users is presented in Table 5.

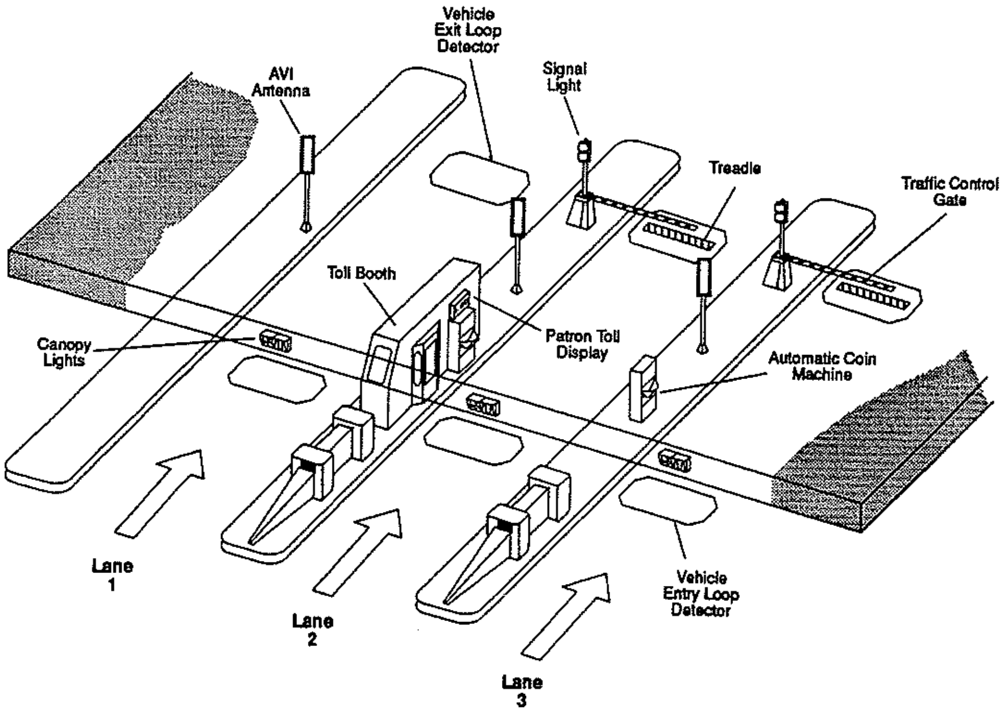


Figure 4. Dedicated ETC Lanes in a Barrier Toll Plaza (14).

Figure 5. Dallas North Tollway (15).

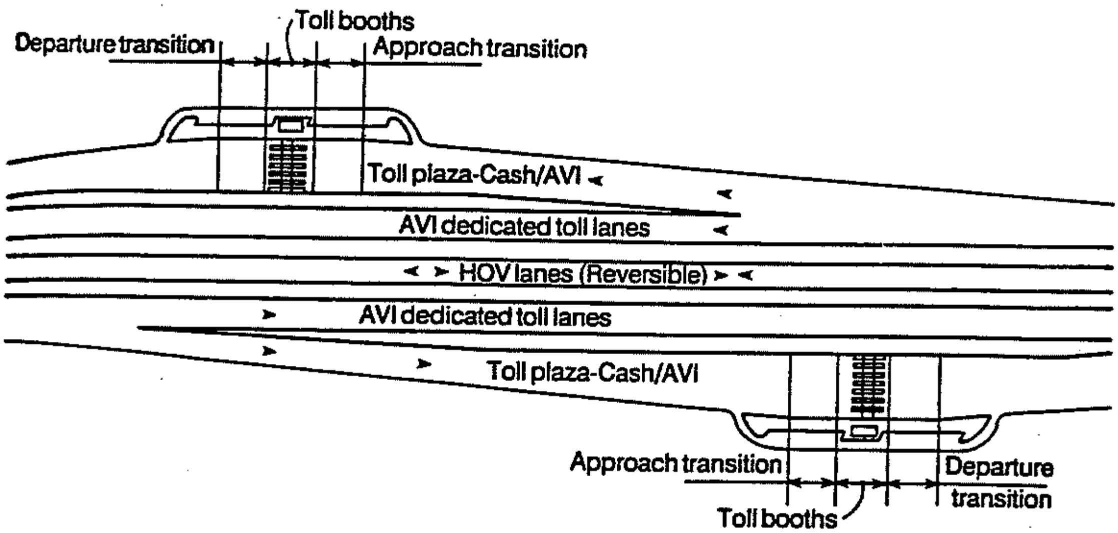


Figure 6. Toll Plaza Design for New Orange County Toll Roads (16).

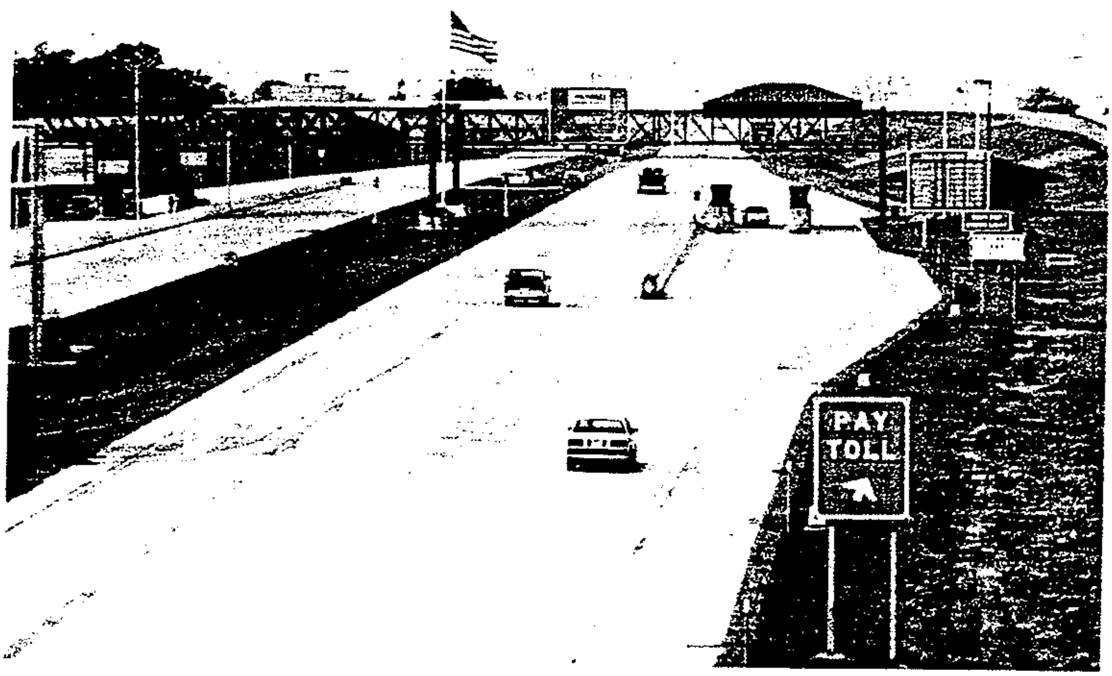


Figure 7. John Kilpatrick Turnpike (17).

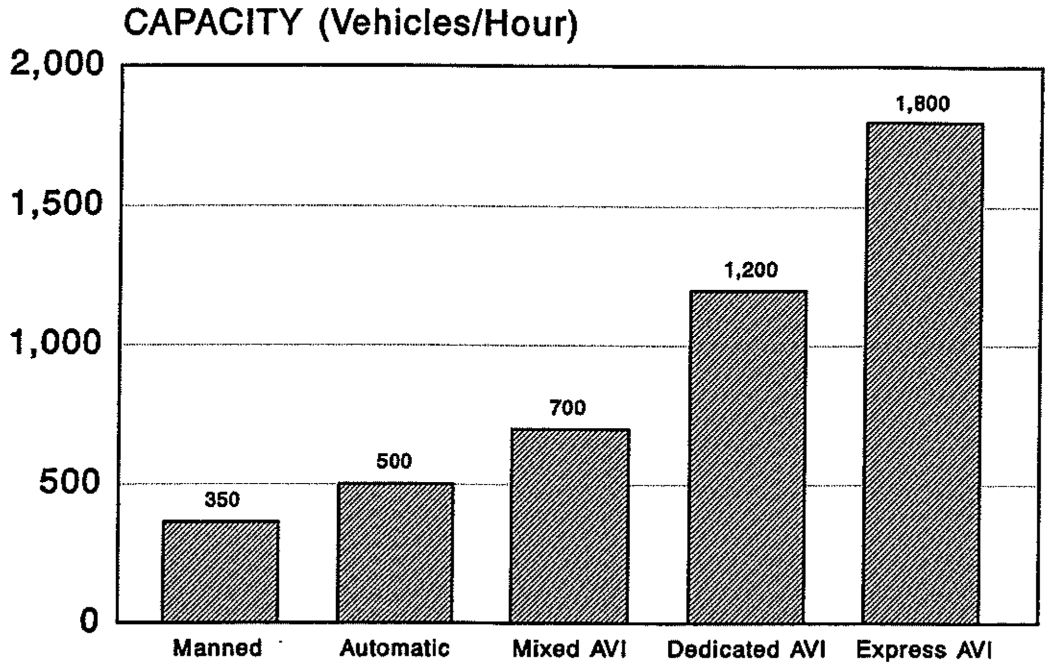


Figure 8. Capacity by Toll Collection Method (8).

Table 5. Payment Systems of Selected ETC Operators (9).

	Premium Toll	Discount Toll	Credit Card	Cash/ Check	Pre-Payment	Post-Payment
Dallas North Tollway	✓		✓	✓	✓	
Lee County, Florida		✓		✓	✓	
New Orleans, Louisiana		✓	✓	✓	✓	
Delaware River Port		✓		✓	✓	
NY/NJ Port Authority		✓		✓	✓	
Grosse Ile, Michigan		✓	✓	✓	✓	
Coronado Bridge		✓	✓	✓	✓	✓
Pinellas County, FL.		✓		✓	✓	
Maryland Trans. Auth.		✓	✓	✓	✓	

Pre-Payment vs. Post-Payment

A pre-payment system requires an established location for opening and replenishing accounts and to process account related mail. The main costs associated with the center include construction or leasing costs, operational costs, computer costs and maintenance costs.

A post-payment system where users are billed monthly for their toll facility usage, would incur additional operating costs for mailing monthly statements and collecting delinquent accounts. This collection process is viewed by many toll authorities as time consuming and undesirable.

Estimated monthly processing costs per account for both pre-payment and post-payment systems based on $25 a month in charges can be seen in Figure 9. From Figure 9, it can be seen that pre-payment systems offer significantly lower processing costs as compared with post-payment systems to the toll operator when considering the potential number of users.

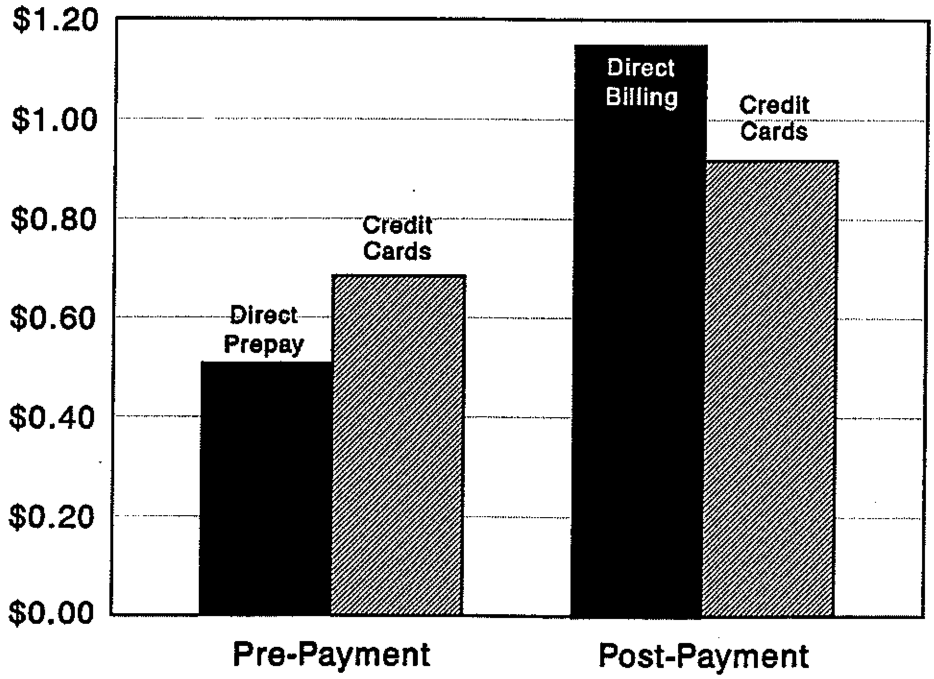


Figure 9. Monthly ETC Processing Costs by Payment Method (9).

Method of Payment

Pre-payment by cash requires the user to visit the ETC center to open an account and subsequently to replenish the account. Pre-payment by check could be accomplished by either visiting the center or through the mail. Pre-payment by cash or check requires some effort by the user to either keep track of account balance or to periodically check with the ETC center and obtain account balance in order to maintain an adequate balance. Some toll authorities will mail the user a notice to replenish the account when the balance reaches a certain threshold.

Pre-payment by electronic funds transfer would only require the user to visit the ETC center once to open an account. An agreement is signed to allow the automatic transfer of funds once a pre-set minimum balance is reached.

Pre-payment by credit card would also only require the user to visit the ETC center once to open an account. Once reaching a pre-set minimum balance the account is replenished automatically by billing the credit card. Both methods of payment, by electronic funds transfer and credit card, require no effort by the user to maintain an adequate balance.

Premium vs. Discount

Another issue is whether users of the ETC system should pay a premium for this service or should be given a discount. As use of the ETC system offers its users the direct benefits of time savings and convenience, some believe these users should be charged a premium.

Others, however, believe that ETC systems benefit not only its users, but the whole system as well. Nonusers benefit from the removal of ETC system users from manual toll collection queues and the community as a whole benefits from reduced infrastructure costs and reduced emissions. Thus, in order to promote such benefits and encourage ETC use, discounted tolls should be offered to ETC system users.

Emissions

With the passing of the Clean Air Act Amendments of 1990, reducing vehicular emissions has become an important issue. Excess emissions are created at toll plazas that utilize manual toll collection systems due to idling, deceleration and acceleration.

Vehicles emit a number of air pollutants including carbon monoxide, nitrogen oxides and hydrocarbons which can be detrimental to public health. Carbon monoxide reacts with the blood cells and limits the amount of oxygen that can be transported throughout the body. Certain hydrocarbons react with the nitrogen oxides and sunlight to produce ozone.

The proportions of these pollutants have been found to vary within the emissions stream as a function of vehicle speed as seen in Figure 10. From the graphs, it is obvious that emission levels are much higher for vehicles idling that vehicles traveling at 55 mph. Emission levels shown in Figure 10 correspond to uniform speed emissions. Emission levels under conditions of acceleration and deceleration were found to be higher for all three pollutants.

By incorporating an ETC system, vehicles can travel at normal speed through the toll plazas and significantly reduce the emissions at toll plazas. In large metropolitan areas this emission savings when multiplied over the number of toll plazas in the region could be an important contribution to reducing ozone and carbon monoxide levels.

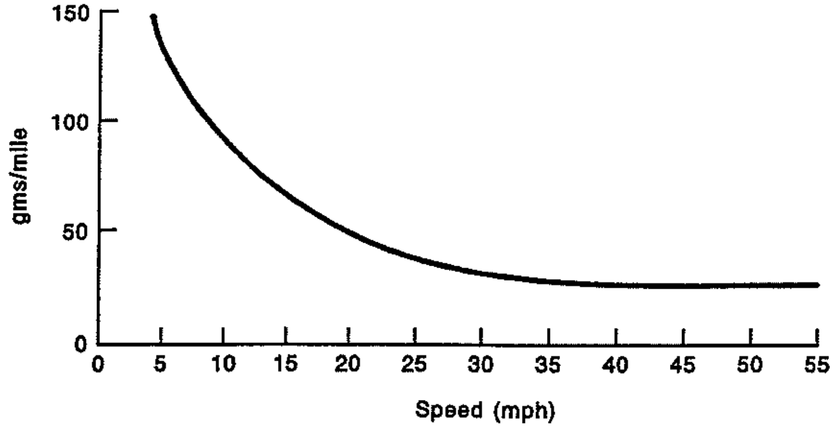
Standardization

The need for standardization is evident in the northeast where toll facilities are in close proximity to each other and a need exists for users to be able to travel on a number of facilities without requiring a transponder and account for each facility. While technologies aren't yet standardized, there is a growing trend towards regional standardization.

An Interagency Electronic Toll and Traffic Management Group has been formed by toll agencies in the states of New York, New Jersey and Pennsylvania which together collect 37 percent of all the tolls in the United States (19). The agencies represented are the Atlantic City Expressway, New Jersey Highway Authority, New Jersey Turnpike Authority, New York State Thruway Authority, Pennsylvania Turnpike Commission, Port Authority of New York and New Jersey and Triborough Bridge and Tunnel Authority. This group is currently in the final testing stages to determine the manufacturer to supply an RF ETC system for the entire region.

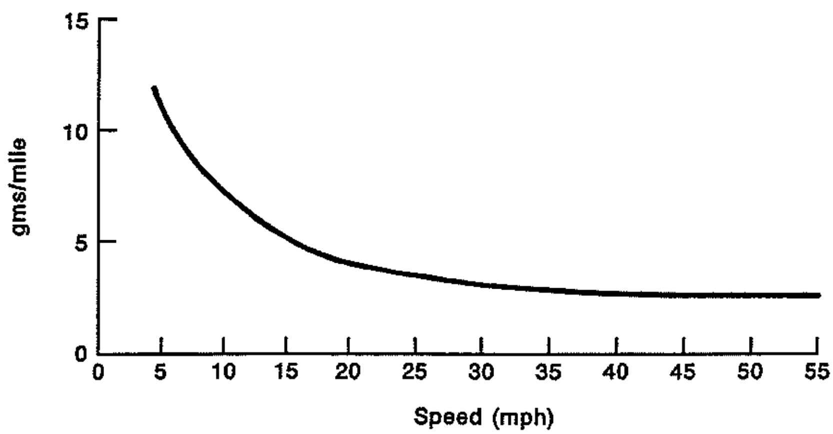
Similarly the Oklahoma and Texas Turnpike Authority have teamed together using similar technology so as to require only one tag and account for a user of any of the system's toll roads.

Some of the issues involved in standardizing ETC are uniform transponder frequencies and enforcement procedures, a common approach to tag placement and compatible system software. The frequency at which RF based ETC systems operate is somewhat already standardized at 915 MHz in the United States and 2.45 GHz in Europe. The main reasons for the selection of these frequencies are to simplify licensing



(a) Carbon Monoxide (CO)

(b) Nitrogen Oxide (NO_x)



(c) Hydrocarbons (HC)

Figure 10. Relationship Between Vehicle Speed and Various Emitted Compounds (18).

Public Perception

Public perception and preferences of several important issues related to ETC systems are presented in this section.

Several results of market research conducted by AT/Comm in 1990 can be seen in Table 6 through Table 8. These results are based on a motorist survey of 900 users of the Lincoln Tunnel, Goethals Bridge, George Washington Bridge and Holland Tunnel (20). From Table 6, the most important perceived benefit of ETC systems is saving time. Eliminating the use of cash from the transaction process was also seen as an important benefit of ETC systems. From Table 7, payment in the form of a check to maintain account balance was preferred by the majority of those surveyed while payment by credit card was the next preferred method of payment. As seen in Table 8, the preferred location of payment was through the mail while payment over the telephone was the next most common response.

The results of a survey to determine the public's willingness to use ETC facilities which either charge a premium toll, a discounted toll or the same toll as a manual lane can be seen in Table 9. These results are based on 2,088 completed surveys of Florida Turnpike commuters (8). With 90.2% willing to use a facility with discounted tolls and only 15.7% willing to use a facility with premium tolls, the role of discounted tolls in encouraging the use of ETC lanes is clear.

In a 1988 nationwide survey conducted by The Urban Transportation Monitor, only 44 percent of those surveyed responded in favored of toll roads as a source of funding when offered a choice. However, when asked if they would support a toll road which incorporated an automatic toll collection system, 85 percent responded in favor (21).

Table 6. Perceived Benefits of ETC (20).

Rank	Rated #1
Save Time	50%
No Cash	40%
Track Expenses	3%
No Rain	.5%
No Benefit Plan	5%

Table 7. Preferred Method of Payment (20).

Rank	Rated #1
Check	58%
Credit Card	27%
Cash	10%
Bank Transfer	5%

Table 8. Preferred Transaction Location (20).

Rank	Rated #1
Mail	49%
Over Telephone	20%
Bank Transfer	18%
In Person	12%

Table 9. Willingness to use ETC (8).

	Yes	No
If tolls were discounted	90.2%	9.6%
If tolls remained the same	67.4%	32.4%
If a premium were charged	15.7%	83.6%

SUMMARY OF FINDINGS

- Toll agencies benefit from ETC systems through significantly lower infrastructure costs and lower operating and maintenance costs.

- Patrons benefit from ETC systems through reduced congestion and delay as well as being provide with an easier method of paying tolls.

- The community benefits from reduced emissions.

- Radio frequency based ETC systems are the most commonly employed ETC technology in the United States and will continue to be for the near future.

- Cooperation between various toll agencies to standardize ETC systems within the region is becoming a more important consideration.

RECOMMENDATIONS

- ETC systems should be implemented in the design of all new toll facilities. Dedicated lanes separated from toll plaza lanes at some distance upstream and downstream of the toll plaza should be designed where possible to maximize the benefits of AVI lanes and increase safety between AVI users and nonusers.

- Implementation of ETC systems should be considered at existing toll facilities as a method of reducing operating and maintenance costs and increasing throughput.

- ETC lanes should be designed as dedicated lanes as opposed to mixed flow lanes to maximize the benefits of the system and encourage patron participation.

- In regions where users are likely to use multiple toll facilities, standardization of ETC technology among the various facilities should be considered.

- Discounted tolls may be an important factor in encouraging drivers to switch to ETC and should be implemented.

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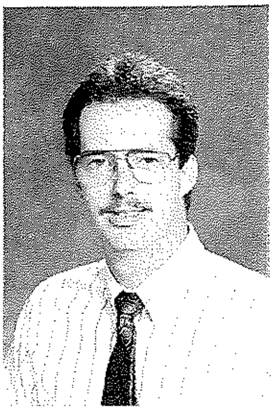

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