Electronic Toll Collection:
A Summary and Analysis of Current Practices with Application to San Juan, Puerto Rico

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Abstract

Toll collection is becoming a more important means for funding of public roadways. A new development in toll collection, Electronic Toll Collection (ETC) is helping toll authorities in the United States by increasing toll plaza capacity without the necessity of expensive expansion. It is also letting agencies offer a more convenient and quicker method of toll payment for patrons.

The various design and implementation issues associated with ETC are presented. Information from the few sources available in the field is consolidated and presented in non-technical terms in order to provide a background for those with little background in electronic toll collection.

A review of five case studies of toll authorities who use ETC is presented. Each facility's vital ETC parameters such as lane configurations and depth of ETC penetration are summarized along with interpretations of how certain parameters affect critical success characteristics of various systems.

Next, simple analysis techniques for capacity and queuing at toll plazas are presented. Data which is commonly available from area transportation models and toll audits is combined with general data from other facilities in order to construct possible ETC lane configurations and the resulting queuing characteristics such as maximum wait time. Calculations are presented which may be executed on a generic spreadsheet program with relative ease.

The queuing and capacity techniques developed are applied to the Massachusetts Turnpike for one plaza. Complete qualitative, queuing, capacity, and costs analyses are presented for tollways in Puerto Rico, with focus on a particular toll plaza.

The principal conclusions from this work are: 1) ETC design information is lacking and a generalized body of knowledge and evaluation technique needs to be developed. 2) ETC systems are generally rated as beneficial and desirable. 3) Increasing capacity through electronic toll collection or other toll plaza configurations is possible, but may increase toll collection costs and clog roadways downstream of toll plazas. 4) The tolling situation in Puerto Rico needs more investigation to make a better decision about the use of ETC on the island.

Thesis Supervisor: Thomas F. Humphrey, Senior Research Associate and Lecturer, Department of Civil and Environmental Engineering

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Explanation of Terms

ACM	Automatic Coin Machine - toll collection machines designed to take exact change (or tokens) from patrons and raise toll lane gate arms. ACM may also refer to the entire lane where an ACM machine is located
ADT	Average Daily Traffic - a measure of average traffic over a 24 hour period - usually refers to weekday averages for systems with peaks occurring during normal daily commute hours - often used interchangeably with Average Daily Transactions
AVC	Automatic Vehicle Classification - a method of classifying vehicles when they pass over sensors in a roadway - usually used for purposes of determining appropriate toll class and charge
Average Daily Transactions	Refers to the number of daily transactions on average through a toll lane, toll plaza, or tolled facility as a whole, often interchanged with Average Daily Transactions (ADT)
AVI	Automatic Vehicle Identification - wireless communications between a transponder mounted on a vehicle and a sensor located at the roadside. Used in toll collection, traffic management, etc. (Often interchanged with ETC - but AVI refers to a wider range of functions)
Barrier Plaza	Toll plaza which extends across the main roadway - all traffic must stop to pay tolls (or pay by non-stop ETC)
Closed Toll System	Toll facility where patrons get ticket at entrance plaza and surrender ticket at exit plaza - tolls are based on distance. Alternatively, ETC can be used, not requiring a ticket to be carried - but is still a closed system
Dedicated ETC	Refers to ETC toll lane which is reserved exclusively for the use of patrons paying by ETC
DNT	Dallas North Tollway
ETC	Electronic Toll Collection - referring to the collection of any toll by means other than cash, exact change, ticket, or token - usually a nonstop tolling process
ETC/ACM mixed	Refers to toll lane with both ETC and ACM payment options used simultaneously - patrons can use either method to pay
ETC/Manual Mixed	Refers to toll lane which has both ETC and Manual toll collection capabilities - used simultaneously - patrons can pay tolls either way
ETC Market Penetration/ Market Share/ Market Use	Refers to the number of patrons on average who pay tolls by ETC. May be an overall number for an entire facility or for a specific toll plaza
ETTM	Electronic Toll and Traffic Management - referring not only to ETC but also to the use of tag/transponder, traffic camera, and loop detector systems for traffic management

	functions
Express ETC	Refers to non-stop high speed ETC toll lanes where vehicles travel at 55 mph or higher and toll is still collected
Express Toll	The Dallas North Tollway electronic toll collection system name
EZPass	The electronic toll collection inter-agency group for the greater New York area including New York State, New Jersey, Pennsylvania, and Connecticut
IBTTA	International Bridge, Tunnel, and Turnpike Association
IPass	The Illinois State Toll Highway Authority electronic toll collection system name
ISTHA	Illinois State Toll Highway Authority
ITS	Intelligent Transportation Systems - referring to a wide body of applications of technology to transportation, including ETTM, ETC, traffic management, collision avoidance, etc.
MassPass	The Massachusetts Turnpike Authority electronic toll collection system name
MassPike	Massachusetts Turnpike Authority or the Massachusetts Turnpike
MPO	Metropolitan Planning Organization
NCHRP	National Cooperative Highway Research Program
Open Toll System	Toll facility where patrons pay fixed amount at barrier or ramp plazas, i.e. not a ticket or closed system
PANYNJ	Port Authority of New York and New Jersey
Ramp Plaza	Plaza on entrance or exit ramp to or from a main roadway where entering or exiting traffic pays tolls
SJMR	San Juan, Puerto Rico Metropolitan Region
TollTag	The E-470 Denver ETC system name
TRB	Transportation Research Board
Tren Urbano	Literally "Urban Train" - refers to the rail rapid transit system being constructed in San Juan, Puerto Rico
VPH or vph	Vehicles Per Hour - number of vehicles processed in one hour at a toll lane, through a toll plaza, or along a section of roadway

Chapter 1

Introduction and Motivation

The purpose of this chapter is to introduce the subject of toll collection to the reader and provide the motivation for the work which is summarized here. The historical place of toll collection along with the importance of toll collection today is presented. Then, a discussion of the difficulty of collecting tolls and new technology which can be applied to toll collection follows. Next, the potential benefits and problems associated with Electronic Toll Collection are summarized. Finally, the motivation for the type of analysis given here and the goals of this paper are outlined.

1.1 Toll Collection as a Historical Financing Method

Toll collection and user fees have a long historical background of providing funding for roads and other transportation systems. In the colonial era, turnpikes and toll roads were private enterprises built, operated, and maintained by private investors. The concept of payment for services rendered at the time of use provided capital for repaying investors and a source of constant revenue, which was very desirable for the building and maintenance of infrastructure. After World War II, many states undertook the building of large, multi-lane highways and charged tolls to pay for them. The money was often raised by issuing bonds whose value was based on future traffic and revenue from tolls. Several of today's inter-city auto turnpikes were built in this manner. In 1956 the Interstate Highway Bill was passed providing funding on the national level for new highways similar to the toll roads, but built using funds from a national gasoline tax. The Interstate System was conceived to connect every major metropolitan area of 50,000 population or more. The era of the Interstate Program lasted from that time until the 90's, when the Interstate Highway Program was finally completed, except for the Central Artery/Tunnel Project in Boston, Massachusetts.

1.2 The Importance of Toll Collection Today

As the U.S. reaches the end of the Interstate funding mechanism and public resources become much more scarce, many proposals for "private / public" funding have come to light. These mechanisms often involve private investment and construction. They allow the investor to run a facility for several years, charging user fees to recover capital and operating costs. Typically at the end of the contract (10, 20, 30 years), the facility ownership is returned to the public entity who commissioned the facility. Other examples return to the pre-Interstate era of states and municipalities funding roadways and charging tolls to cover bonding of such ventures. Current examples of toll roads using these mechanisms are the SR91 toll lanes in California and the Dulles Tollway outside of Washington DC.

The SR91 express lanes project consists of two lanes in each direction added to the median of a 10 mile stretch of SR 91 in Southern California. Completed in 1995, it is entirely privately funded and operates under contract with California DOT. All vehicles pay tolls via electronic toll collection (ETC) and tolls vary throughout the day to keep the lanes flowing free.[1]

The Dulles Tollway was built with private and public funds to connect the Dulles International Airport with downtown Washington, DC. It has three tolled lanes of regular traffic in each direction with two lanes of free roadway in each direction for authorized commercial vehicles and other airport users, including carpools and van pools. Total length is 13 miles.[2]

There are plenty of examples of new toll facilities proposed or being built by public agencies and private/public partnerships. In 1988, the *Urban Transportation Monitor* conducted a nationwide survey on new toll road proposals. Eighty percent of the respondents indicated

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[1] "Private Toll Roads in the United States: A Status Report," *Innovation Briefs, Urban Mobility Corporation*, Vol. 7, No. 1, February 1996.
[2] Michael C. Pietrzyk, "Electronic Toll Collection Systems," *Curbing Gridlock: Peak-Period Fees to Relieve Congestion*, Transportation Research Board Special Report 242, pg. 492.

that their metropolitan area was actively planning toll roads or would be in the near future.[3] In 1996, there's an ever growing interest in toll roads such as the Transportation Corridor Agency (TCA) projects in California and the Dulles Greenway, an extension of the Dulles Tollway, in Virginia. Clearly the future holds several new toll roads for the United States.

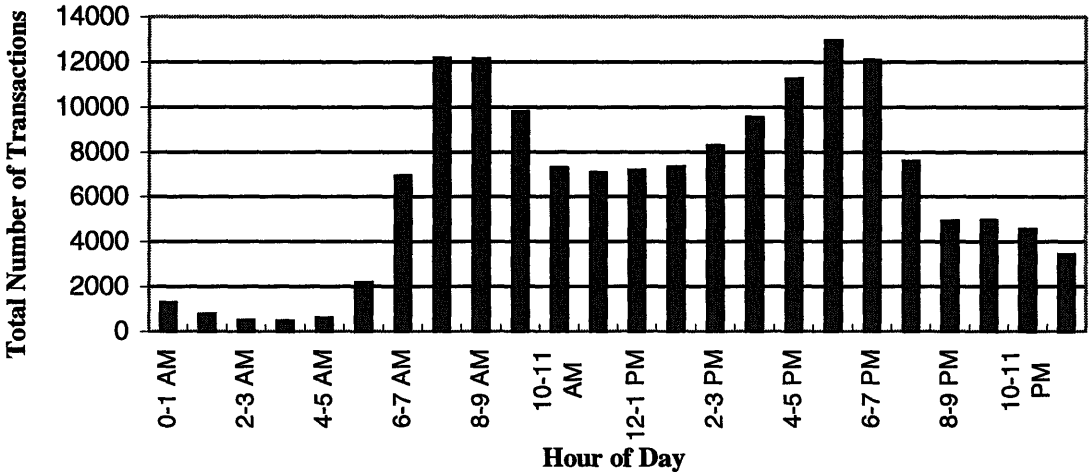
1.3 Difficulty of Collecting Tolls

There are four factors contributing to the difficulty of collecting tolls on roadways. First, for barrier type toll plazas, all traffic must come to a complete stop to pay the toll, since the barrier extends completely across the roadway. This can be a serious safety hazard if drivers are falling asleep or do not slow down fast enough. For example, the Connecticut Turnpike (Interstate 95) removed tolls on its roadway in 1987 primarily due to a seven fatality accident at this type of toll plaza.[4] Although many new measures are available for avoiding these accidents, such as better signing, information, and enforcement, it is still a major concern.

Second, building toll plazas large enough to accommodate demand without queues is largely infeasible because peak demand is usually many times greater than average demand. In addition, plazas in urban areas are often geographically constrained by high land values, environmental considerations, and construction costs. As an example of peaking, Figure 1.1 shows the demand characteristics for the Massachusetts Turnpike (MassPike) Extension throughout the day. Because of the peaking characteristics of facility traffic, queues typically form at toll plazas. For large urban connectors, bridges, and tunnels, these can be very long (1 to 2 miles in some cases) causing wasted time to society and additional pollution. As evidence of these queues, Figure 1.2 shows the average speed on the Massachusetts Turnpike Extension during peak periods. Notice that the primary slow downs and congestion occurs at the toll plazas.

[3] T. Hugh Woo and Lester A. Hoel, "Toll Plaza Capacity and Level of Service", *Transportation Research Record*, No. 1320, pg. 119.
[4] Amar Kanaan, *An Economic/Financial Analysis of Implementing Electronic Toll Collection and Traffic Management Systems*, M.S. Thesis, Massachusetts Institute of Technology, May 1992, pg. 90.

Figure 1.1
Toll Transactions at MassPike Extension Allston/Brighton Plaza for Average Weekday

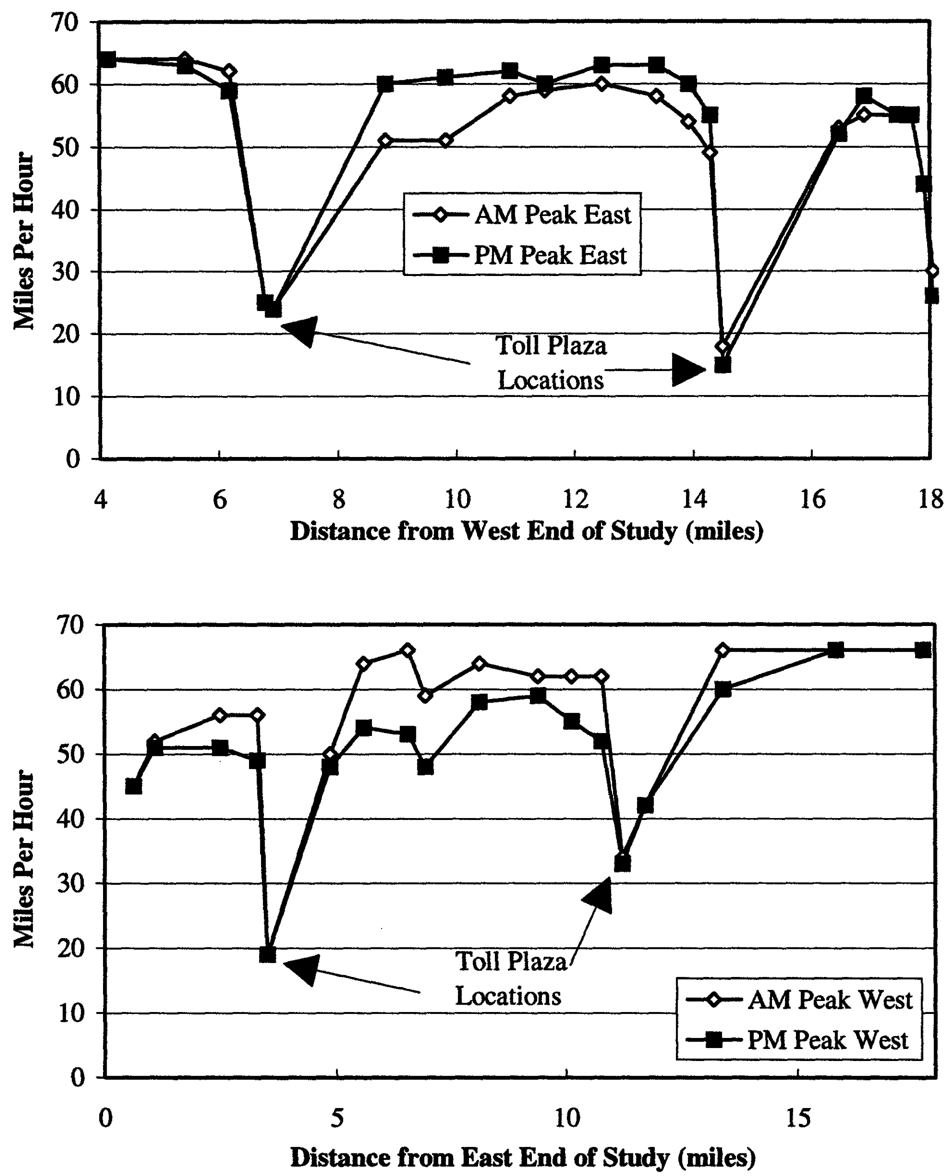


Source: Massachusetts Turnpike Toll Audit Department, 4/4/96 Hourly Counts

Third, collecting cash, processing change, and accounting are very expensive and time consuming processes. The making of change at toll lanes and counting money takes time. Labor must be employed to collect and count tolls, accounting for a large part of the expense of toll collection. For Automatic Coin Collection Machines (ACMs), the cost of collection is greatly reduced while enforcement problems increase. Also, security against robbery both at the lane and during processing at the plaza is costly.

Fourth, customers are inconvenienced by toll plazas. Customers must slow down and stop, weaving through merge areas, and wait in queues. Typically, customers must carry change (often exact change), or a pass book, or tokens, and hand over some form of payment at the booth. Some must then wait for change from attendants and/or a barrier arm to rise. Finally, they must go through an acceleration and merge area after the plaza. For these reasons alone, customers often dread toll plazas.

Figure 1.2: Average Speed Along MassPike Extension



Source: *Central Transportation Planning Staff,* Boston Massachusetts, Spring 1994.

1.4 New Technology (ETTM, ETC, AVI, ITS)

New technology has emerged to help mitigate the problems associated with toll collection, including transponder/tag systems, electronic funds transfer, and other advanced technology. These systems are referred to by many different names including: Electronic Toll and Traffic Management (ETTM), Electronic Toll Collection (ETC), Automatic Vehicle Identification (AVI), and more generally as Intelligent Transportation Systems (ITS). Typical systems are of the transponder/tag type (see Chapter 2 for a full explanation) which can identify a specific vehicle as it passes some point on the roadway. Another technology, Electronic Funds Transfer, has emerged from the banking industry and can be used to transfer money electronically from users to the toll agency and from toll agencies to banks. Advanced technologies in this field includes smart cards, high speed transactions, axle count in motion, weigh in motion, and high speed video capture. Together, these advances are providing the means for building new toll financed facilities with less inconvenience and costs than older systems. In addition, older toll facilities are being converted to new technologies to take advantage of the benefits associated with these new technologies.

Currently, 10 of the 55 toll agencies in the U.S. are collecting tolls automatically through these new technologies. Some 441,000 vehicles are equipped with ETC technology nationwide, and 6% of the average daily traffic on toll facilities across the U.S. is using ETC technology.[5]

1.5 Potential Benefits

ETC technology may have many benefits for both the toll collection authority, the toll patron, and society. The two primary benefits to toll authorities are increased capacity without expansion and reduction in labor costs. In theory, ETC may be able to increase current capacity by up to 250% (depending on depth of ETC usage and pre-ETC collection methods) without the need for expensive expansion. For instance, one lane converted from a manual

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[5] Neil D. Schuster, "ETTM Technology: Current Success and Future Potential", *ITS America 1995 Annual Meeting*, pg. 2.

lane to dedicated ETC in Florida showed an increase in throughput of 154%, from 500 to 1270 vehicles per hour (vph).[6] This is primarily due to the non-stop nature of traffic through the lane. Even at plazas with only one dedicated ETC lane and several mixed lanes, significant capacity increases are possible (see Chapter 5 for more on capacity analysis.) Labor costs can be reduced by eliminating the need for toll collectors in some lanes. For instance, ETC on a previously manual lane can save an entire lane of labor costs. This is especially beneficial where Automatic Coin Machines are not feasible, such as where tolls are greater than approximately $1.50 or on a ticket "closed toll" system. However, there are of course, other costs associated with ETC that are not associated with non-ETC lanes. (see section 3.4.2 for more analysis of costs.)

There are several other benefits to toll agencies. These include lower maintenance cost of ETC systems, better security of funds, increases in road safety due to the non-stop nature of ETC, lower pollution due to shortening queues with faster processing, time value of money on deposits, positive public image, better traffic management, better data acquisition, bond rating improvements, and use of creative design strategies. Some of these are described as follows.

Funds Security

There is some information which shows that the percentage of collected revenues may be less than 100%.[7] This can be attributed to toll evasion by patrons, which is less frequent with gated systems; incorrect amount of toll paid, whether intentional or not; change lost around the toll booth area; losses from handling of cash from toll booth to bank or robbery; and inaccurate counting of large quantities of change.

Safety

Increases in road safety are largely due to the non-stop nature of traffic through the toll plaza with ETC systems. Stopping and starting several times while waiting in line is not necessary.

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[6] H. M. Al-Deek et al., "Evaluating the Improvements in Traffic Operations at a Real-Life Toll Plaza With Electronic Toll Collection", submitted to *Transportation Research Record*, December, 1995, Figure 3.
[7] Amar Kanaan, *An Economic/Financial Analysis of Implementing Electronic Toll Collection and Traffic Management Systems*, M.S. Thesis, Massachusetts Institute of Technology, May 1992, pg. 58.

On newer facilities, such as SR91 in California, there is no toll booth, only a toll area which looks like normal high speed roadway. This virtually eliminates the possibility of a patron missing the slow down signs and crashing into the toll booth or a queue waiting for the tolls. However, there are some safety concerns associated with ETC. See section 3.3.3 for a more detailed explanation.

Pollution

Lower pollution can be obtained from shorter queues at toll plazas by utilizing the increased capacity that ETC provides. Less idling time means less pollution. The agency benefits by less criticism of pollution around toll plazas and by a better working environment for employees.

Time Value of Money

Provided an ETC system is pre-pay, the money deposited early for tolls can collect interest for the agency until the toll is used by the patron.

Public Image

Public image for toll authorities can increase since many patrons are aggravated by long lines, carrying money, and the general age of many toll plazas. This is especially useful today when many patrons are clamoring for the removal of tolls on older roads since bonds have generally been paid off in the last decade or so. Introducing ETC helps to alleviate these patron aggravations and promote the agency as acting in the patrons' best interests. Acceptance of new toll roads can be increased by ETC systems since potential patrons cite the aggravation of stopping for tolls as a primary disincentive for supporting new toll facilities. For instance, a survey conducted in 1991 in the Boston area showed that public support for toll roads in the future increases with the use of ETC. See Table 1.1 for results.

Table 1.1
Support of Toll Roads in Boston Area

	Oppose Toll Roads	Neutral	Support Toll Roads
Without ETC	55%	21%	24%
With ETC	29%	29%	42%

Source: Kanaan, A, *An Economic/Financial Analysis of Implementing Electronic Toll Collection and Traffic Management Systems*, M.S. Thesis, Massachusetts Institute of Technology, May 1992, pg. 64.

Data Acquisition

Better data acquisition and traffic management are possible by having more detailed information on the movement of vehicles around toll plazas and on the highway (if, for instance, tags are used determine traffic flow patterns).

Bond Ratings

As public and patron approval increases, it is likely that traffic may increase on the roadway. Also, security of funds, as mentioned above, is improved. Both of these effects can lead to increases in bond ratings and ultimately, cost savings.

Creative Design

Finally, more elaborate road pricing schemes can be realistically implemented, such as congestion pricing and class pricing. Such creative design strategies are viewed as essential to the future of congested roadways.

Patron Satisfaction

Customers, on the other hand, find ETC systems more convenient in not having to carry cash, tokens, or tickets; by being able to set automatic billing through credit cards; and by not having to decelerate, stop, and accelerate on the roadway. Most importantly, waiting time for dedicated ETC lanes is greatly reduced. For instance, a dedicated ETC lane in Florida experienced a drop in average waiting delay from 1 minute, to zero (due to the non-stop nature - no delays are experienced.)[8] Another benefit is a reduction in the amount of gasoline used since patrons presumably no longer wait in long queues.

<u>Societal Benefits</u>

There are also some benefits to society, such as reduced noise and air pollution due to lower total idling of automobiles, and less land encroachment from not needing to expand toll plazas. However, these benefits are not major factors influencing decisions on whether or not to implement ETC on a facility.

1.6 Potential Problems

There are several potential problems that can arise from the use of Electronic Toll Collection. First, on crowded roadways, the toll plaza's bottleneck may be acting as a regulator limiting the flow downstream. ETC could make the situation worse by releasing more traffic into already congested areas. (However, note that adding new traditional toll lanes would have the same effect.) Second, the capital outlay and operation costs of the ETC system may exceed the financial benefits from reduced labor and funds security due to low ETC usage rates and higher back office accounting and distribution costs for ETC. Finally, there may be technological problems with a large number of inaccurate tolls collected (misreads, double reads, slow speed requirements) and violation enforcement.

Potential problems for other groups include patrons, who may find the initial cost of entering the program too high, and society in the form of toll collectors union's whose jobs may be replaced by ETC.

Table 1.2 provides a summary of the potential problems and benefits of implementing ETC systems.

[8] H. M. Al-Deek et al., Figure 8B.

Table 1.2
Effects of Implementing ETC

	Increased Throughput	Additional Payment Method	Other Effects
Authority	-less need to expand -better public image -meeting objectives (safe and efficient mobility) -safety improvements -less pollution -potential increase of violations -potential downstream backups	-increased security -time value of money	-traffic management -data acquisition -increased acceptance of toll roads -bond rating improvements -initial costs high, but lower than other collection types -decreases in operating costs -potential for creative design strategies
Patrons ETC Users	-time savings -fuel savings	-convenience	-safety -impact of design strategies -perceptions -initial cost
Patrons non-ETC users	-time savings		-perceptions
Society at large	-increased acceptance of toll roads -lower environmental impact -lower congestion	-increased acceptance of toll roads	-safety -union's reaction -initial cost of system -new demand for facility -impact of design strategies

Source: Kanaan, A, *An Economic/Financial Analysis of Implementing Electronic Toll Collection and Traffic Management Systems*, M.S. Thesis, Massachusetts Institute of Technology, May 1992, pg. 49, augmented.

1.7 Motivation for "State of the Art" Summary and Simplified Analysis

It has been discovered by the author that the amount of information for design, evaluation, and operation of toll plazas available publicly is relatively slim at this time, (See Chapter 2.) Due to the resurgence of interest in toll financing for roads and the advent of ETC technology, new interest has formed in the field. However, most work is being done on a facility specific basis by private consulting firms. Clearly the need exists for a "state of the art" use and design summary. In addition, simplified analysis for current toll facilities is needed for toll authorities who are just beginning to look into Electronic Toll Collection without the necessity of hiring a private consulting firm. Furthermore, a general body of knowledge is needed to advance research in the field.

1.8 Goals of Thesis

The goals of this research are to explain the current state of ETC design and use in the United States, develop a method of simple analysis for proposed ETC systems, create a "first approximation" queuing model for individual plazas, and apply lessons learned to toll roads in Puerto Rico.

Chapter 2

Literature Review, Research Methodology, and Scope of Thesis

The purpose of this chapter is to describe the literature available in the field of Electronic Toll Collection, describe the research methodology used, and outline the scope of the thesis.

2.1 Literature Review

As mentioned above, a review of the literature in the Electronic Toll and Traffic Management (ETTM) realm has revealed, surprisingly, a relatively small amount of literature on the subject. Although the transmission and technology area for ETC, generally found under electrical engineering, seems to have a relatively large amount of published work, very little systems integration information, level of service (LOS) standards, evaluation information, and operations information is available. Indeed, Woo and Hoel in a 1991 paper on toll plaza capacity and level of service have said, "Most roadway design features (such as freeway lanes, ramps, and intersections) have nationally accepted level of service (LOS) standards, but the Highway Capacity Manual is silent on the subject of LOS standards at toll plazas, and no national design guidelines exist."[9]

There are primarily two reasons for the lack of literature and information on the subject. First, toll collection capacity design and level of service analysis, for the initial toll roads built in the United States, was never homogenized into a general body of knowledge. Second, most ETC systems integration is currently being performed by transportation consulting companies who's work is naturally proprietary. In addition, their work (currently) is not generally applicable since contracts are executed individually and represent facility specific information.

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[8] T. Hugh Woo and Lester A. Hoel, pg. 119.

However, the role of consulting firms is important from a funding and knowledge point of view since it is very costly to develop toll authority level expertise for this type of analysis.

Information that is currently available is in the form of a few documents published by the Transportation Research Board (TRB), the National Cooperative Highway Research Program (NCHRP), the International Bridge, Tunnel, and Turnpike Association (IBTTA), ITS America, and others. (See Bibliography for a complete list.)

As the body of knowledge in the ETTM field, and in the Intelligent Transportation Systems field in general, increases there is likely to be more generalized information on analysis and integration available. Part of the work of this document is to synthesize a compilation of this general knowledge at the time of writing as well as to present a picture of some of the systems in use in the United States.

2.2 Research Methodology

The methodology used to conduct this research is a straightforward approach of collecting current knowledge, augmenting knowledge with case studies, application of basic equations to situations, and application of all knowledge gained to a specific study of a particular situation. First, all literature available to the author on the subject of toll collection and Electronic Toll Collection (ETC) was reviewed and important information summarized. Then, a specific set of toll facilities were chosen for a survey. The survey was based on elementary questions in the field of toll collection and ETC. The set of chosen facilities was surveyed, and the toll agencies which responded were then summarized into case studies. Next, basic analysis techniques were synthesized based on literature, case studies, and mathematical equations. These techniques include toll plaza capacity analysis, queuing and level of service analysis, and cost analysis. Finally, all the information was used in an analysis of a specific situation which directly relates to the sum of the research.

2.3 Scope of Thesis

The method of analysis developed is designed for a simple overview or first approach of ETC systems. It is intended to be performed with information readily available to most toll agency engineering planners in order to assist in deciding if building an ETC program will be cost effective and useful to the agency and its patrons. It involves mostly qualitative analysis and simple mathematics. It does not attempt to perform full cost/benefit analysis, queuing theory, demand theory, or design. Detailed analysis is best performed by expert consulting firms in the field due to the relatively infrequent necessity for full analysis and high level of expertise needed for such analysis.

The method given will rely on case studies of United States ETC systems which were surveyed for information on ETC usage ranges, lane configurations, type of roadway, tolls collected, discounts offered, system successes, etc. as well as the general knowledge available in the field.

A queuing model developed late in the paper is based on straight forward capacity analysis available to most authority planners using simple, deterministic structures. It produces proposed time and cost savings as well as tests lane configurations. The queuing model will be calibrated on the Massachusetts Turnpike and then applied to a single toll plaza in Puerto Rico.

Thus, the information available on ETC is thin, but this paper attempts to make some contribution to the field, thereby increasing this body of knowledge.

Chapter 3

Overview of ETC

As mentioned in the Literature Review, there is relatively little published general information on ETC. The purpose of this chapter is to present a consolidation of the information which is available. Following the format of what has been published, this section will attempt to provide a broad overview of ETC technology, system design considerations, institutional and implementation issues, privacy and legal issues, and systems testing.

3.1 ETC Technology

ETC technology generally involves some type of attachment to the patron vehicle, such as a tag or sticker, and a transmitter/receiver array at the tolling location. The technology can be classified by data interchange type and data interchange method.

The available data interchange types are read-only, read-write, and smart card, usually classified I, II, and III respectively.

Type I (or "read only") systems pick up some type of identification information from the vehicle mounted component such as account number, vehicle classification type, and vehicle fleet designation (such as private, United Parcel Service, or Roadway Trucking.) The receiver then looks up the patron account and deducts the appropriate toll for that class of vehicle at that location. For a barrier or open system, this is suitable because tolls are charged on a flat basis when the patron's vehicle crosses a specific point on the roadway. However, for ticket or closed systems, this type poses a problem. Here, tolls are charged based on the patron's entrance and exit points to the facility. However, the equipment in a Type I system does not know where the vehicle entered the toll facility since there is no portion of memory on the patron's ETC equipment which can hold this information. The equipment is "read-only."

Thus, the distance based charge cannot be evaluated. (On a Type II systems, a portion of the memory can be "written" on, recording the entrance location, as described below.) One possible solution to this situation is to look up the patron's account in real time and determine if the vehicle is just entering the system and, if so, record the entrance time and location in the main computer account. If the vehicle is leaving the system, on the other hand, the entrance information can be retrieved from the account record and the appropriate toll calculated and deducted from the account. Unfortunately, such a scheme involves real time (or near real time) transfers of vast quantities of information between all toll plazas on the facility, complicating equipment requirements and accounting, or involves later account resolution, complicating enforcement and accounting. However, Type I systems are still widely in use, (see case studies.)

Type II (or "read-write") systems read identification from the vehicle mounted "tag". If the system is open, the toll is deducted from the patron's account, and the remaining balance is often written to the tag. An alternative use of Type II is to have the balance stored on the tag itself, the balance read, toll deducted, and balance written back to the tag. This facilitates anonymous tags thereby alleviating privacy concerns. On a closed, distance based pricing facility, if the vehicle is entering the system, the entrance time, location, and lane are written to the tag. Upon exiting the system, the writable portion is read and the toll computed and deducted. The "entrance" notation is removed from the tag, readying it for another "entrance." Type II systems typically have more memory than Type I systems and have a higher data communications rate allowing for more error checking to take place while the vehicle is in communications range. Of course, they also require more sophisticated communications algorithms and data checking to make sure the correct information was written to the right tag. Currently, there are only two systems in the United States that claim to run ETC systems on a closed tolling system. These are the New York State Thruway and the Kansas Turnpike.[10]

[10] *Toll Roads Newsletter*, "E-tolling rolls out rapidly in New York", No. 3, May 1996.

Type III systems use "smart card" technology. Smart cards have a much larger memory bank than Types I and II, as well as a microprocessor. The tag portion of this system is usually a small card with a vehicle mounted reader that performs the communication with the transmitter/receiver array. Other Type III tags are single units with an integrated smart card. In addition to all of the functions for Types I and II, the smart card system can compute tolls and display remaining card balance. Also, the card system can be used as a general clearing house to pay more than tolls, such as parking fees and transit fares. However, there are currently no such integrated systems in use. Type III systems have the advantage of being more robust than the other systems since failure of a section of memory on a lower type tag will render it inoperable whereas a Type III tag can move information to other non-damaged areas in the memory and continue to function.

Table 3.1 provides a summary of the three types of ETC systems.

Table 3.1

Summary of Electronic Toll Collection Types

Type	General Characteristic	Advantages	Disadvantages	Cost
I	read only	-simple communications, simple tag	-unable to record information for closed toll systems	low
II	read - write	-can record entrance location and time for closed toll systems -can contain account balance	-more complex communications and tag	medium
III	smart card	-can record more information than Type II -can do some transaction calculations -can display current balance -can be used on an integrated payment systems	-even more complex communications and tag	medium - high

3.2 Technologies Available

Five basic technologies are available for ETC and AVI: optical license reader, optical bar code, inductive loop, surface acoustical wave, and radio frequency/microwave.

Optical license readers have been available for some time, used to identify speeding motorists in various countries. For ETC use, these systems take a video picture of a vehicle's license plate and process the data to identify the license number and state. This information is then used to deduct tolls from a user account or a violation is issued if the plate is not a valid ETC customer. The advantage of this type is that no special tag is required and licenses are difficult to duplicate. However, these systems are very slow since a great deal of data processing is needed, leaving time for only one reading of the license, not leaving time for a second or third error resolution reading. Also, the variety of weather, license location, vehicle cleanliness, and lighting has generally made these types of systems unfeasible due to a high rate of mis-readings. Finally, note that this is a Type I system, as described earlier.

Optical Bar Code technology is somewhat of an improvement over optical license plate readers. A larger version of a UPC-type barcode is printed on a sticker which is then attached to a particular position on the vehicle, usually on the driver's side rear window or front left bumper. A laser based scanner then reads the code and performs the toll transaction. The primary advantage is that the barcode is a one dimensional data imaging routine which takes much less time to resolve and the bar codes are fairly cheap to produce at $1-$2 per sticker.[11] However, the stickers are easier to duplicate. These systems are also subject to the vagaries of weather, location, cleanliness, and lighting. They also have typically tight limitations on the speed of the vehicle passing through the toll plaza. These types of systems have been used successfully on some facilities in the U.S. Again, this is a Type I system.

Inductive loop technology takes advantage of the counting and detection loops already available at most toll facilities. The "tag" is attached to the bottom of the vehicle and read through the inductive loop. The tags are typically active, requiring their own power source.

The primary advantages are the loop infrastructure currently in place and the close proximity of the tag to the reader reduces the possibilities of interference and "double" or "cross lane" mis-reads of the tag. (Note, however, that the optical methods above have little or no chance of these types of mis-reads.) The primary disadvantages of Inductive Loop technology are a slower data rate - although high enough for error checking, vehicle power required, less convenient installation, and some sensitivity to environmental conditions. This technology can be Type I or II (and possibly III, but RF communications has generally become the technology of choice before the development of a Type III inductive loop system.)

Surface Acoustical Wave (SAW) technology uses the power from the transmitter/receiver electromagnetic wave to set up an acoustical wave along the surface of a lithium crystal. Periodic strips on the crystal reflect the energy to the receiver in a sequence that can contain data. The advantages are that the tags are relatively cheap to produce, are virtually impossible to duplicate, and no power is required to operate the tag. The disadvantages are a relatively short reading range, low transmission rate due to the conversion of electromagnetic waves to mechanical waves, and once manufactured, the tag cannot be reprogrammed by anyone. SAW also is a Type I system.

RF/microwave systems can be classified into two types: passive and active. The communications technology is generally a standard microwave transmission. Passive tags use the "backscatter" method whereby the transmitter/receiver is continuously broadcasting while a tag passing through this area will reflect back a modulated RF signal which can be read and identified. Typically these systems do not require power and are not very complex. Tags are hard to reproduce, but are more expensive ($10-$50) than the previously described technologies.[12] They have a high communications rate, allowing for error checking. Passive systems are subject to interference from other RF sources, as discussed below, and have a shorter range plus lower reliability than active tags. They are typically Type I and II.

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[11] Michael C. Pietrzyk, pg. 478.
[12] ibid.

Active RF tag systems use onboard power (either the vehicle power or a battery) and are triggered by the interrogation beam from the transmitter. The information is then transmitted by the tag to the receiver. They have a greater operating range, better reliability, and less chance of interference due to the stronger, self-powered RF beam than passive tags. They also have a high communications rate. They are usually the most expensive type of tag, have a greater possibility of "double" or "cross" reads, and need a power source. These systems can be Type I, II, or III.

In general, the technology of choice currently is active RF tags using small internal batteries. These batteries are designed to last five years or more.[13] Type I systems are typical. Type II and III have not seen much use. Table 3.2 gives a summary of technologies available for ETC use.

[13] Conversation with Massachusetts Turnpike Officials, May, 1996.

Table 3.2

Electronic Toll Collection Technology Summary

Technology	General Characteristics	Advantages	Disadvantages	Cost
Optical License Plate Readers	reads license plate numbers and letters directly	-no special tag needed -hard to duplicate -low chance of interference from other lanes	-type I only -slow data processing rate -highly subject to errors due to weather, location, lighting, cleanliness	-very low
Optical Bar Code	reads bar-code sticker	-tags are cheap -medium data processing rate -low chance of interference from other lanes	-type I only -easy to duplicate -highly subject to errors due to weather, location, lighting, cleanliness	-low
Inductive Loop	uses inductive loops already installed at most toll facilities	-antenna system already in place -medium data processing rate -low chance of interference from other lanes -type I or II	-tag requires power source -tag harder to mount -somewhat subject to weather, location, lighting, cleanliness	-medium
Surface Acoustical Wave	uses an acoustical surface wave on a lithium crystal to bounce back vehicle identification to reader	-tags are cheap -tags are virtually impossible to copy	-short reading range -low transmission rate -cannot be reprogrammed after manufacture -type I only	-low
Passive Radio Frequency/ Microwave	reflects back modulated RF signal to the antenna broadcasting signal	-high data processing rate -hard to reproduce -type I or II	-subject to RF interference from other sources -lower reliability than active RF tags	-high
Active Radio Frequency/ Microwave	uses internal power to send reply signal to antenna	-high data processing rate -hard to reproduce -low interference from other sources -types I, II, III	-chance of cross-lane reads are higher than passive -require on board power source	-high

3.3 System Design

There are, of course, many issues to consider when designing an ETC system. Since most technical aspects of the system are the concern of the equipment manufacturer, they are not covered here. Instead, the issues more pertinent to toll authority planning officials are covered.

3.3.1 Overall architecture

The overall architecture of an ETC system is pictured in Fig. 3.1 as conceptualized by the author. The overall characteristics of the "Transmitter/Receiver" and "Tag" blocks have already been examined above in "Technologies Available".

A "Lane Controller" monitors traffic through each toll lane and coordinates the toll transaction process. For manual lanes, the controller is usually a simple device recording vehicle presence, treadle axle counts, calculation of toll due (especially for ticket systems), type of payment, toll paid, and transaction date and time. The controller also controls the lane open/closed process, canopy and channelization lights, toll display, and barrier arms. Manual and mixed manual/automatic coin collection have a collection personnel interface of some type. The lane controller usually communicates with a plaza or system-wide computer relaying transaction and accounting information to the master accounting system.

For an automatic coin lane, the controller has a similar function as a manual lane, but will raise a gate automatically after payment is verified to let the patron pass.

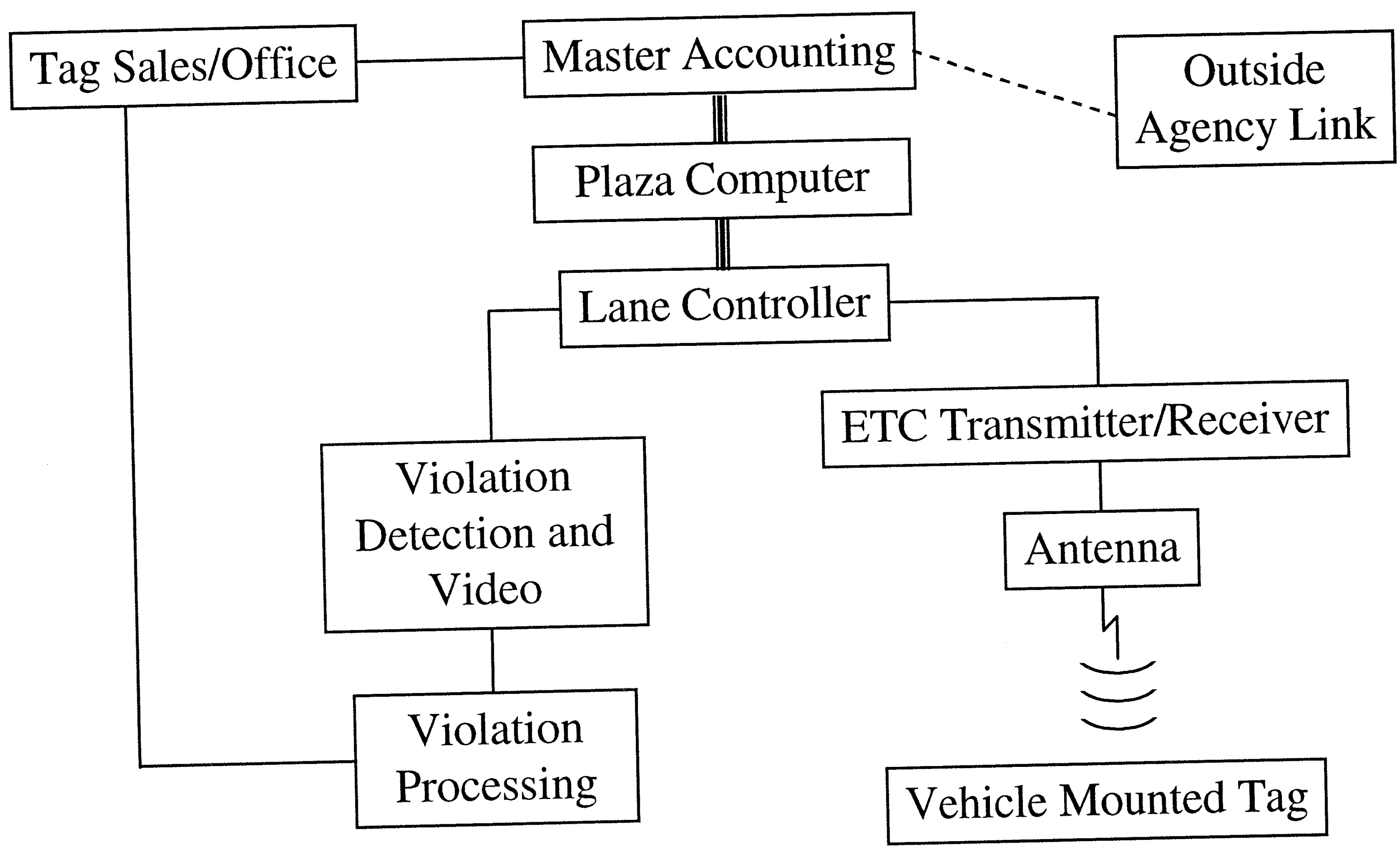
For ETC lanes, the lane controller process becomes somewhat more complicated. The transmitter/receiver communicates with the lane controller which has a periodically updated account listing. The transaction is verified and recorded and the appropriate signals to the driver indicated (e.g. "Go - Tag Valid") or a violation is noted, and the violation camera is activated, and the appropriate signals indicated (e.g. "Call Tag Office"). The controller periodically downloads all of the transaction and violation data to the plaza computer. Note that periodic downloading from the lane controller to the plaza computer and from the plaza computer to the lane controller requires a large amount of memory for tracking and verifying account status in the lane controller. Alternatively, the account verification and transaction information can be done in real time with the lane controller communicating with the plaza computer, lowering the lane controller memory requirements.

On many older toll facilities with retroactive fitted ETC systems, there is a separate computer controlling the ETC transaction which reports the results to the lane controller or another computer. On some systems, there is no link to the lane controller. Thus, the original lane controller may report a violation when a valid ETC transaction took place or the ETC system may report a violation when a valid traditional transaction took place. In this case, the ETC system computer is connected directly to the master accounting office, usually through a separate link than the normal infrastructure. This can cause account resolution and tedious downloading problems, but replacing the entire toll collection system with an ETC compatible system which does not have these problems can be prohibitively expensive.

The "Violation Detection and Video System" usually consists of a high speed digital video camera oriented to record license plates of violators. Violations can be vehicles without ETC tags, vehicles with overdrawn balances, vehicles with malfunctioning tags, vehicles with stolen or improper class tags, etc. The license picture with the date, time, and lane location information is recorded and sent to "Violation Processing".

"Violation Processing" assembles the transaction and video information to make a complete record of the violation. Sometimes the violation is merely an account below balance and the master accounting office is directed to initiate a funds transfer from the patron either automatically or by billing. Other violations involve illegal use of the lane which must be turned over to the government policing agency for ticketing and collection through regular traffic violation channels. (See Section 3.5.1 for more information.)

Figure 3.1
Electronic Toll Collection System General Architecture Conceptualization (for radio frequency technology)



The "Plaza Computer" records the information from all the lane controllers and ETC sub-systems if connected, which is then reported to a master accounting system. The plaza computer also receives information from the master accounting system on account balances. However, this information may be directly downloaded to an overlay ETC system. Plaza computers often communicate only periodically with the master accounting office, necessitating that all account information be stored on the plaza computer for use in real time.

The "Master Accounting Office" collects all toll transaction information and reconciles accounts. It either runs or communicates with the tag sales office. It may also communicate with "Outside Agencies" if joint agreement for use of a common tag technology exists across several agencies in a system, usually through the other agencies' master accounting offices.

The "Tag Sales Office" is in charge of account opening, deposits, replenishment, tag distribution, and billing operations for the ETC part of the system. Some agencies call these offices "tag stores" and some have more than one store.

All of these parts together form the ETC system.

3.3.2 Accuracy and Reliability

Accuracy and reliability with ETC systems is becoming less of a major issue as technology advances in the field. In general, most systems are specified to have reliability of no more than one error in 10 million reads.[14] However, certain key factors affect these results.

First, interference from other radio frequency (RF) sources has been a concern with RF based ETC systems for some time. Cellular phones, 2-way radios, and radar that operate at or near ETC frequencies can interfere with transmissions. A dedicated frequency may be obtained from the Federal Communications Commission (FCC) by getting a license. However, the permitting and fees associated with this process are prohibitive. Without a license, FCC regulations require that all RF systems "must accept any interference that may be received including interference that may cause undesired operation."[15] In addition, the FCC requires that operation not interfere with other licensed users, especially those of higher priority.

A second factor affecting reliability is tag installation and system geometry. Tags which are misaligned, poorly located, or simply not in the vehicle can, of course, cause inaccurate reads and violation indications for valid accounts. These can be reduced by proper patron instruction. System geometry can cause other forms of interference. For instance, transmissions from nearby ETC lanes at the same toll plaza can cause interference or "cross lane" readings where one lane's transmitter/receiver communicates with a tagged vehicle in a neighboring lane. Toll both physical geometry, field strength, transmitter power, and tag power can all contribute to interference. Most of these problems are being eliminated by ETC equipment manufacturers by better design practices and using well designed specialty antennas which are capable of focusing transmissions in a tightly defined field pattern.

A third factor is weather, heat, humidity, and moisture. Although these factors are more of a concern for older technologies such as optical bar code, they still play a problem with some systems. As will be noted in the Lincoln Tunnel case study in Chapter 4, moisture can get into externally mounted tags causing them to fail over time.

3.3.3 Health & Safety

Electromagnetic transmissions have been the topic of much discussion in recent years with regard to health and radiation exposure. Concerns are being raised about prolonged exposure to various radiation sources. ETC systems, however, have a much lower power level than most of these sources. Indeed, considering the length of exposure to patrons is one second or

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[14] ITS America, *Electronic Toll & Traffic Management (ETTM) User Requirements of Toll Operating Authorities for Future National Interoperability*, June 12, 1995, pg. 1.

less, and considering they will be at least one meter from the transmitting antennas, the radiation exposure is several orders of magnitude below Occupational Safety and Health Administration (OSHA) standards. More frequent exposure to toll collection personnel is again not an issue due to the fairly low power of the transmissions necessary for ETC.[16]

Another issue in toll collection personnel safety is the necessity on some facilities of crossing lanes of traffic to get from operator booths to the plaza building. There is an obvious concern that patrons passing through express ETC lanes cause a significant safety hazard in this regard. Proper training, caution signs, and speed limits through ETC lanes, especially for retro-fitted lanes can increase safety. Newly built or re-built toll plaza geometries designed to accommodate high speed ETC transactions frequently are on the main roadway, with an exit type structure for non-ETC collection, thus eliminating this hazard. Other facilities have overhead or underground personnel connection corridors from toll lanes to the plaza building to avoid this problem.

Finally, the approach of vehicles not planning to stop at the toll plaza is of concern. Mixed use ETC lanes, involving both stopping for traditional toll collection and non-stop ETC use can be a problem given that an ETC patron will not know if the vehicle in front of him will stop or not. This can be eliminated by avoiding use of these types of lanes and making sure approach signage is clear. Hence, roadway and plaza geometry is very important when considering ETC application. For new toll plaza structures, as mentioned above, traffic mix is less of a problem as non-ETC patrons are instructed to exit, which is a normal process most drivers are used to, while non-stop ETC users drive along regular roadway with antennas installed over it, eliminating speed concerns.

3.3.4 Traffic Operations

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[15] NCHRP Synthesis 194, *Electronic Toll and Traffic Management (ETTM) Systems*, Transportation Research Board, 1993, pg. 9.
[16] ibid, pg. 11.

Lane mix

A primary concern with ETC systems design is the correct number and types of lanes to accommodate the different kinds of patrons using a toll plaza. Fortunately, being a major design factor, a significant amount of research has been performed in this area. Throughput for a plaza is based on the mix of open lanes and the mix of traffic approaching the plaza. Dedicated and dedicated express ETC lanes can accommodate from 1200 to 1800 vph. Manual lanes usually accommodate around 350 vph and automatic coin lanes around 500 vph.[17] However, if use of ETC is low, then having a large percentage of dedicated ETC lanes is detrimental since traditional toll patrons will be forced into longer lane queues while ETC lanes go relatively unused. Hence, installing a large percentage of ETC lanes to increase capacity is faulty. Instead, the proportion of ETC and manual lanes needs to be adjusted to meet traffic mix.

Since the topic of lane mix is fairly long, involving lane mix, traffic mix, throughput, gates, and other topics, it is covered much more completely in Chapter 5.

Table 3.3

Volume Thresholds for ETC Implementation, Peak Direction

Initial Consideration for Mixed ETC	3,000 vehicles per hour
Initial Consideration for Dedicated ETC	5,000 vehicles per hour
Initial Consideration for Express ETC	7,000 vehicles per hour

Source: *Electronic Toll and Traffic Management (ETTM) Systems*, NCHRP Synthesis 194, Transportation Research Board, 1993, pg. 14.

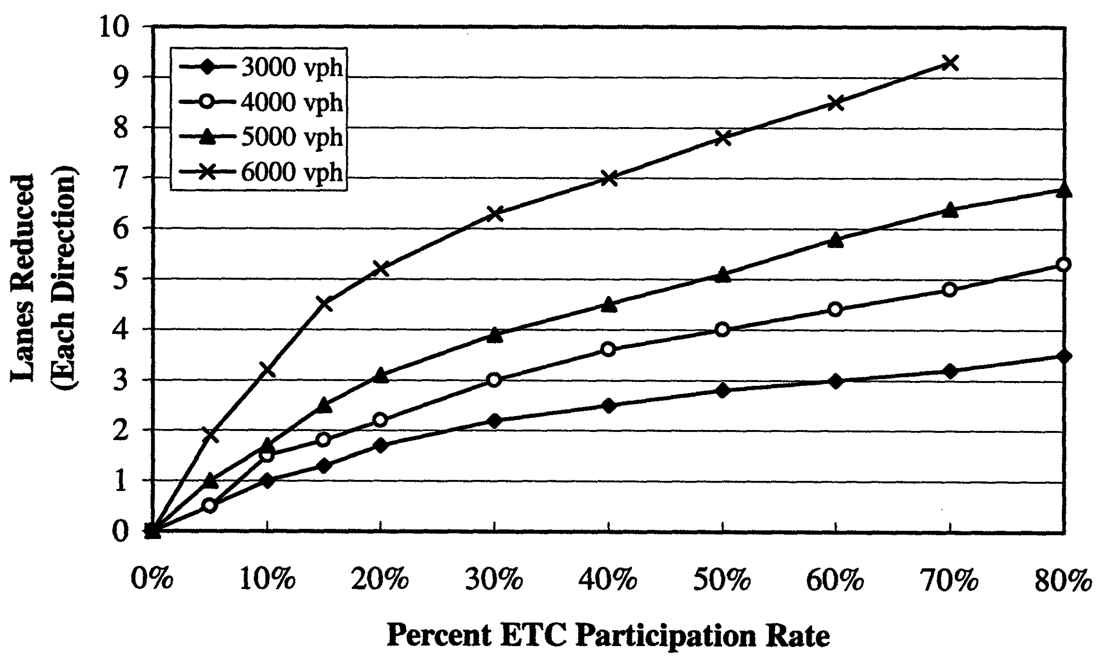
Minimum Thresholds of Demand

Despite the need to at least perform a simple analysis of the queuing and lane mix for ETC installation, certain minimum thresholds of demand have been determined for consideration of ETC. These are summarized in Table 3.3. Based on these figures, at least 3,000 vph demand

[17] ibid, pg. 12.

must exist at a toll plaza for a significant part of the peak hour to consider ETC. This is based on toll plaza simulation and the benefits gained through usual ETC participation rates. A more precise presentation is shown in Fig 3.2, which shows the potential for lane reduction, given ETC participation rates and peak hour demand levels. This information provides a quick check for agencies considering ETC. (Although, it must be stressed that a complete analysis of the capacity and queuing situation at a plaza must be performed to actually determine lane reduction potential. See Chapter 6 for an example.)

Figure 3.2
Plaza Lane Reduction Potential
(As a function of peak hour vehicles per hour)



Source: Electronic Toll and Traffic Management (ETTM) Systems, NCHRP Synthesis 194, Transportation Research Board, 1993, pg. 12.

Signaling and Channelization

Signaling and channelization for patrons approaching toll plazas can be difficult. Frequently, patrons maneuver to get in the correct type of lane, depending upon how they intend to pay, then choose among appropriate lanes for the shortest queue. This requires proper lane markers well in advance of the toll plaza. The addition of ETC usually increases the choices from two types (manual and automatic) to three types (adding ETC) making the decision process more difficult. The situation is complicated by the current driver unfamiliarity with ETC.

Many systems have developed logos for their ETC systems, such as "E-Z Pass". (See Figure 3.3 for an example.) Selection of color coding for the three types of lanes and large signs are frequently helpful. It is generally viewed that manual collection should be to the far right, automatic coin in the middle, and dedicated ETC to the left, since people are used to left lanes being non-stop or passing lanes in regular traffic, while right lanes are slow lanes in regular traffic. The reference from which Fig. 3.3 is taken presents one applied solution to these difficulties.

3.3.5 Service and Maintenance

Although few ETC systems have been running long enough to estimate service life and maintenance cost, it is estimated that ETC lanes cost about 10 to 20 percent less in maintenance than regular lanes.[18] Usually, service contracts and emergency response is specified as part of toll system acquisition. For instance, in the case of the Massachusetts Turnpike, a repair time of two hours is required for equipment failures which directly affect revenue collection or impair audit capabilities, as called for in an request for proposal for a new collection system.[19]

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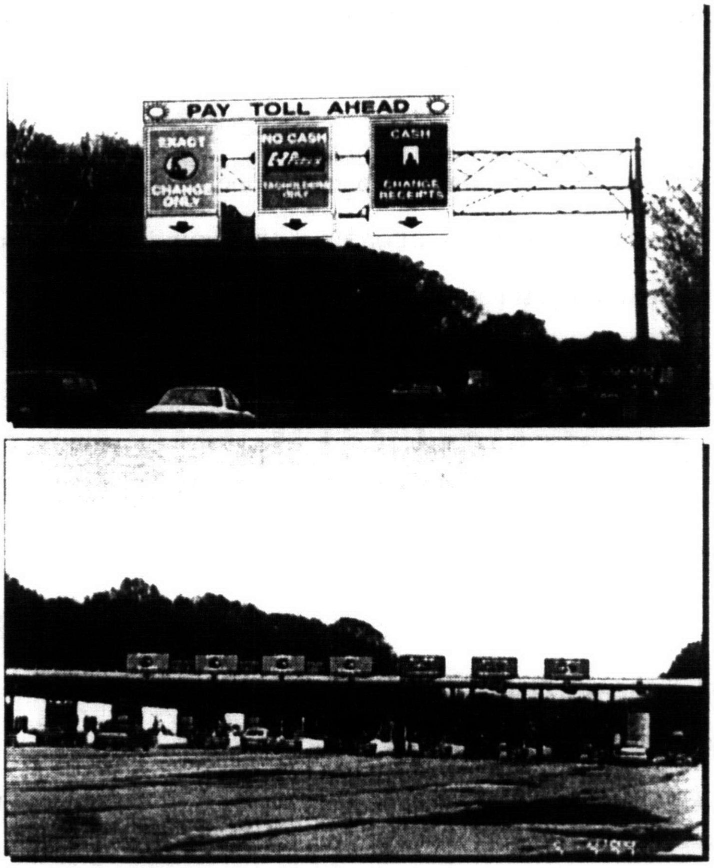
[18] ibid, pg. 15.
[19] Massachusetts Turnpike Authority, *Toll Collection System Upgrade and Related Services: Request for Proposal*, June 1995, pg. II-33.

Figure 3.3: Example of Sign and Logo for ETC System



Recommended Signage

Source: Thomas Harknett, "A Low Tech Solution for a High Tech IVHS Problem", *Computing in Civil Engineering, Proceedings of the Second Congress*, Volume 1, June, 1995, pg. 90.

3.3.6 Accounting, Tag Distribution, Back Office

Issues in design of accounting, tag distribution, and back office support are heavily related to system configuration, size, payment options, etc. For instance, master accounting can be handled by one office with just one tag store if the authority operates one toll plaza. However, for several toll plazas stretched over a wide geographical area, several tag stores may be called for. Distribution of tags is typically done through one or two stores located close to a particular toll exit, and via mail order. Other options include selling tags at a major toll plaza in a off-line building, if such space is available.

3.4 Institutional and Implementation Issues

3.4.1 Agency Goals

Clearly the goals of the toll authority which have precipitated interest in ETC are important to system requirements, design, and use. For some authorities, the desire is to create a more convenient payment method for regular patrons. The natural action in this case would be to develop ETC as just another form of payment, convenient to patrons, and probably only utilizing mixed ETC lanes. Another goal may be to increase plaza capacity without expansion or even decreasing the number of lanes needed. In this case, dedicated ETC lanes and marketing for a high percentage of ETC use is appropriate. A third goal is to reduce overall collection costs by reducing labor, (see Section 3.4.2.) Again, high market penetration and dedicated lanes are indicated. However, if the costs for ETC marketing and accounting are too high, the savings in collection in labor may be outweighed by these and other back office and accounting costs. Hence, it is necessary to view the design of any ETC system from the perspective of the desired goals throughout the process of acquiring an ETC system.

3.4.2 Cost

Probably the most common question asked by toll authorities looking into ETC systems is, "How much will it cost?" The answer is much more complicated than the question. Costs can be broken down into two categories: capital cost and operations and maintenance (O&M).

Capital costs for ETC systems are around $15,000 to $35,000 per lane for equipment. This does not include any civil engineering changes. However, most ETC systems have little civil engineering changes that need to be made, except for signage and cabling. It also does not include capital needed to start up an ETC program such as advertising, market research, tag office/distribution, tags, plaza computer, host computer, and accounting costs.

Table 3.4 presents a comparison of lane equipment costs for the different types of toll collection lanes. Here it is noted that the costs for ETC lane equipment is much cheaper than manual, automatic, and manual/automatic mixed lanes. However, this can be deceiving since other capital costs associated with ETC are not taken into account, such as tag costs. Table 3.5 covers the additional capital costs associated with ETC lanes. Note that some of the costs are systems wide.

Table 3.4

Equipment, Operating & Maintenance Costs by Lane Type

Lane Type	Lane Equipment Costs per Lane	Operating & Maintenance Costs per Lane
Manual	$58,500	$141,900
Automatic	$58,000	$43,300
Manual/Automatic	$107,500	$111,000*
Manual/ETC	$72,700	$146,100
Automatic/ETC	$69,500	$47,500
Manual/Auto/ETC	$121,300	$115,200*
ETC Dedicated	$15,400	$4,200
Express ETC	$15,400	$4,200

*Based on operation at 16 hrs manual & 8 hrs Automatic Coin
Source: NCHRP Synthesis 194, Table 5, pg. 33.

Using the information on unit capital costs, it is possible to calculate total capital costs for a system, to a first approximation using a method suggested and outlined by R. Gobeille.[20]

Table 3.5 **ETTM Unit Capital Costs**		
Item	**System Requirements**	**Cost**
ETC toll lane (equip. only)	per lane	$25,000
Plaza Computer	per plaza	$165,000
Host Computer	per system	$300,000
Enforcement system	per system	$100,000
Systems Integration	per system	$400,000
Tags	per ETC patron	$30
Initial Marketing	per system	$100,000
Signage	per plaza	$8,000

Source: NCHRP Synthesis 194, pg. 25,26; Gobeille, Table 4, pg. 6; Boesch, Electronic Toll Collection Survey, Texas Turnpike Response.

Table 3.6 is such an analysis for an 18 lane, single plaza system with two dedicated ETC lanes and two ACM/ETC lanes. The analysis assumes a retro-fitted toll plaza with other toll collection facilities already in place, and no additional lanes being added. New ETC lanes are converted from other types, such as automatic coin.

It can be seen that, the initial cost of buying an ETC system for a single plaza is in the millions. Note that the most expensive item is tags. In most systems, there is a deposit required for the tag. The time value of these deposits may be used to offset this cost, but the deposits cannot be used directly for tag purchase. Also, for a single plaza system, the host and plaza computers may be combined, with a lower price around $200,000.[21]

[20] Richard J. Gobeille, "How much will ETTM Cost You? Maybe Not As Much As You Think", *IBTTA 62nd Annual Meeting Proceedings*, November 2, 1994.
[21] ibid, Table 4.

Table 3.6 **18 Lane, Single Plaza ETC Capital Costs**			
Item	requirements	cost per unit	cost
ETC Toll Lane	4	$25,000	$100,000
Plaza Computer	1	$165,000	$165,000
Host Computer	1	$300,000	$300,000
Enforcement System	1	$100,000	$100,000
Systems Integration	1	$400,000	$400,000
Tags	24,000*	$25	$600,000
Initial Marketing	1	$100,000	$100,000
Signage	1	$8,000	$8,000
Total			$1,773,000

*Based upon 90,000 daily transactions, 25% market share approx.

The other cost is in operations of ETC lanes. The obvious cost savings here are in labor. Table 3.7 suggests some round figures for ETC maintenance, enforcement, transaction costs, and tag store operations.

Table 3.7 **ETC Operational Unit Costs (annual)**		
Item	**System Requirements**	**Cost**
Maintenance	per lane	$2,350
	per plaza	$20,000
	per system	$50,000
Enforcement Operation	per system	$145,000
Transaction Cost	per transaction*	$.02
Tag Store	per system	$220,000

*based on $.02 average transaction cost for credit card transactions and/or funds transfer and/or bank accounting fees

Source: IBTTA 62nd Annual Meeting, *How much will ETTM Cost You? Maybe Not As Much As You Think*, R. Gobeille, Table 8, pg. 9

Capital depreciation for computer equipment is usually assumed at about 5 years (or shorter) due to the changing computer market. However, most toll authorities do not replace equipment nearly that often. For instance, the Massachusetts Turnpike RFP for a new toll collection system specifies a design life of 15 years.[22] Therefore, an average of 10 years will be assumed. For the 18 lane plaza example with four ETC lanes, Table 3.8 shows the annual operating cost, including this depreciation. (Note that the per lane maintenance cost is $2350 in Table 3.7, whereas in Table 3.4, O&M costs are estimated at $4200 per lane. Hence, Table 3.8 uses an average of these two values, which are estimates from two different sources.)

Table 3.8
ETC Operational Costs - 18 lane plaza example (4 ETC lanes)

Item	System Requirements	Unit Cost	Total
Maintenance per lane	4	$3,300	$13,200
per plaza	1	$20,000	$20,000
per system	1	$50,000	$50,000
Enforcement Operation	1	$145,000	$145,000
Transaction Cost	6,600,000*	$.02	$132,000
Tag Store	1	$220,000	$220,000
Depreciation (10 yrs.)			$181,500
Total Annual Cost			$761,700

*Based on 330 base days per year (little use on ½ of Sundays), 20,000 tag transactions per day (84% of all tag holders daily)

Thus, a first analysis of an 18 lane toll plaza yields an annual operating cost of about $800,000 for an ETC system with 4 lanes. Note, however, that the operating and maintenance costs associate with the automatic coin collection aspect of the mixed ETC/ACM lanes are not included in this analysis - because it is presumed the mixed lanes are already automatic coin lanes, hence there is no incremental cost increases associated with the operations.

[22] Massachusetts Turnpike Authority, pg. III-24.

One of the key factors in cost analysis is depth of ETC participation. For greater use of ETC lanes, cost per transaction decreases since ETC capital depreciation is spread out over more transactions. Table 3.9 shows an analysis from the Oklahoma Turnpike Authority. Note that the break even level, where the cost of transaction is the same for both cash and ETC, is at 25% market penetration. Hence, it is important that this breakpoint be eventually reached in any system. Notably, systems will differ in the location of this break point. For instance, systems with a high rate of automatic coin collection may have a lower average cost per transaction, leading to a much higher break point, even to the extent that this breakpoint cannot be reached by the ETC system.

Table 3.9

Oklahoma Turnpike Authority Estimates for Costs per Transaction at Different ETC Market Penetration Levels

	Cost Per Transaction	
Usage Level	Cash	ETC
0%	$0.26	N/A
10%	$0.26	$0.74
20%	$0.29	$0.37
25%	**$0.315**	**$0.315**
30%	$0.32	$0.25
40%	$0.38	$0.19
50%	$0.43	$0.15
60%	$0.44	$0.12

Source: Kanaan, Oklahoma Turnpike, pg. 82.

The cost analysis presented above is certainly a first approximation review. For a more complete analysis and example of cost calculations (including non-ETC lanes and personnel), please see Chapter 7.

3.4.3 Ownership Arrangements

There are several forms of ETC system ownership and operations options, many of which are used throughout the United States by toll authorities.

The first, and perhaps most common, is the authority ownership option. Typically, a toll authority will hire a systems integrator to work with them in designing purchasing requirements and working out design issues. Then, the system is purchased from the vendor directly, usually through a bidding process. Toll authority personnel run the plaza system, staff the tag store, run accounting, and are involved in violation processing. The vendor provides maintenance and warranty coverage. Under this type of agreement, the authority maintains complete control over all aspects of toll collection and keeps all profits earned on toll deposits. However, the authority must also re-train individuals (or hire new employees) to run the new service; and it must put forth significant capital outlay for equipment, which cannot be recovered if the ETC system is later abandoned before full depreciation.

A second arrangement would be to contract out ETC in a concession arrangement. Here, the authority hires a contractor to design and install equipment using its own capital, operate the system (collect tolls), and turn revenues over to the agency with the contractor fee taken off the top. The advantage of this arrangement is that the authority need not put forth the capital expenditure for equipment which is likely to be obsolete in 5 years. Also, additional personnel (for operations, violation enforcement, accounting, and tag store operations) and expertise is the responsibility of the contractor. However, the authority must also monitor the contractor for auditing purposes. The authority can define performance objectives for the system and the contractor or provide incentives for the contractor to expand ETC market share through per-transaction based payment. Finally, the authority would usually loose the time value of pre-paid ETC accounts to the contractor.

A third arrangement would be a lease of the equipment from the vendor. In this case, the authority would work with a systems integrator and vendor to define needs/requirements and obtain suitable equipment from a vendor. The authority then leases the equipment, retraining its own personnel to fulfill the necessary operations, accounting, and tag store roles. Equipment is typically owned by the authority at the end of the lease. The advantage of this arrangement is a much lower capital cost for equipment (although over the length of the lease, cost of the equipment may actually be more than purchasing options), retaining control of toll collection processes, retaining access to value of the deposits, and still have the ability to end the lease and get another supplier without being forced to keep purchased equipment. Of course, several versions of this option are available, with as little or as much control as wanted by the authority.

As mentioned, the first option appears to be most common at this time. However, future innovative leasing arrangements, as capital becomes harder to obtain, may appear in the future.

An innovative approach to toll collection has been suggested recently among some agencies. Since the toll authority's primary goal is to pay off bonding debts and operate the roadway, they are likely to not want to be involved in the technical aspects of managing the toll collection process. Note that most toll authorities are public agencies and are subject to complex litigation from hardware suppliers in the matter of ETC equipment procurement. A recent case in Massachusetts provides an excellent example where a manufacturer argued with the authority that procurement documents were clearly written to exclude the manufacturer's equipment, which is against state law. State agencies can get into costly legal battles on these types of issues, and have very little power to win their case. Alternatively, an authority could hire another private entity with expert experience in money handling and accounting to collect tolls and process accounts, such as a bank. It is likely that a private company would not have problems with procurement and would be much more able to defend itself if a manufacturer tries to sue the private company. In addition, the private company would have much more latitude in the purchase of ETC equipment and be able to update equipment frequently, even switching manufacturers as needed, with relatively little notice by the toll authority. Unfortunately, no one has explored this type of arrangement, so the cost and benefits have not be estimated.

3.4.5 Patron payment

Patron payment options are a primary consideration in ETC systems. Options include cash, personal check, electronic funds transfer (EFT), and credit cards. Typically, at least cash and personal checks are used today. However, some systems have started ETC operations allowing only credit card payments, limiting the range of patrons who can use ETC. Payment options are a consideration in both toll payments and in tag deposits (if one exists.) It is likely that with a greater number of payment options, more ETC penetration will be achieved.

Another issue to be decided is pre-payment or post-payment. In pre-payment systems, patrons will typically put a balance of tolls on their account when it is opened. If the amount of money in the account falls below a certain level ($15, $10, or $0 for example), the authority is allowed (by written agreement) to replenish the account through transfers or requires the patron to deposit more money for tolls. Until the account is replenished, violations are noted at the plazas if the patron uses the ETC system. Prepayment systems typically do provide monthly itemized statements, if the user requests, for a small monthly fee.

In post-payment systems, transactions are recorded and itemized bills sent each month to the patron. The toll authority looses the time value of deposits in this system. There are also the additional costs of overdue account collection.

It would seem obvious that a toll authority would prefer pre-payment and patrons would prefer post-payment. Interestingly, pre-payment is actually preferred by patrons as noted in Florida and Oklahoma.[23]

Another consideration in patron payment is toll levels and classes. Three options are available: premium tolls, existing tolls, and toll discounts. Advocates of premium tolls for ETC patrons have noted that customers are likely to pay extra money for the convenience of

[23] NCHRP Synthesis 194, pg. 24.

using ETC, especially if express ETC lanes are available. In addition, collection by ETC may be more expensive than traditional automatic coin collection methods, the additional charge used to offset this difference. Advocates of existing tolls argue that ETC is just another payment method, that costs of ETC systems will balance with savings in labor and automatic coin collection, and that, unlike premium and discount tolls, bonding documents need not be reviewed for permission. Advocates of toll discounts argue that toll collection is cheaper by ETC and that users need some incentive to use ETC given the additional time in obtaining a tag and cost for the deposit (if one exists.) Also, toll discounts may provide incentive for more patrons to use the tollway, thus making up for the discounts offered.

In general, increases and decreases in tolls will require review of bonding arrangements in order to assure security of revenue. Typically, bonding agencies will require a full traffic and revenue analysis, which is costly, to approve such changes. However, many toll authorities have found toll discounts to be useful and beneficial, the extra effort worthwhile.

Equity becomes an issue with differing toll rates and tag deposits. Toll authorities must be careful not to discriminate against users by charging high deposit fees then offering toll discounts as this precludes those who do not have the high deposit fee from benefiting from the discounts. Also, having limited payment options, such as credit card payment only, can discriminate against certain patrons and may be at issue with bond reviews for ETC implementation.

3.4.6 Inter-agency Cooperation

In metropolitan areas, more than one toll authority often exists. Since ETC is likely to be used on more than one facility, coordination between agencies is a must. At the very least, agencies must arrange operating frequencies and tags as not to interfere with each other. However, it is more beneficial for agencies to cooperate and make systems in one regional area compatible with each other. Thus, patrons on one system can pay tolls on other systems electronically. As mentioned in section 3.1, master accounting systems of different agencies would have to have some kind of account resolution procedure for such operation.

Currently, the EZPass system in the New York City area is a multi-agency group coordinating electronic toll collection over a massive system of roads, bridges, and tunnels. Only a few facilities in the area have ETC options available, but the details of inter-operability have been worked out among the group's members. For a detailed explanation of the New York area EZ Pass Inter Agency Group, see *Things to Consider When Multiple Toll Agencies Share ETTM Customers* by M. Caldwell.[24]

Another innovative project in this area is the coordination between the Dulles Tollway and the newly opened Dulles Greenway near Washington, D.C. Here, customers will open an account with either facility and be allowed to universally use one tag on both systems. This program was scheduled to begin operations in early 1996.[25]

3.5 Privacy and Legal Issues

3.5.1 Enforcement

At major issue on ETC systems is enforcement. Enforcement refers to the method used to assure that ETC lane patrons pay the appropriate toll and penalize those who do not. Currently, there are approximately three ways in which toll payment is enforced on ETC systems: gates, enforcement agents, and high speed video and tape.

Gates are currently in use on automatic coin lanes and on some manual collection lanes. They are activated either automatically or manually. They have been shown to be effective at enforcing toll payment, but evaders still exist. Some toll authorities have to replace several gates broken by toll evaders a day. With regard to use on ETC systems, it is certainly

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[24] Marion L. Caldwell, Jr. and Michael Zimmerman, *Things to Consider When Multiple Toll Agencies Share ETTM Customers*, IBTTA 1995 International ETTM Symposium, pg. 103-110.

plausible to use a gate. Once the ETC transaction is verified, the gate is automatically raised and the motorist proceeds. If the ETC transaction takes place sufficiently before the gate, the system can raise the gate with nearly non-stop operation of the patron vehicle. Unfortunately, this causes a lot of timing and driver hesitation problems, not to mention toll evaders trying to piggy back or jump in front of valid ETC vehicles. Also, slowing to stop for a gate adds approximately 1 to 1.5 seconds to processing time for an ETC transaction.[26] Finally, being mechanical, when gates fail or are snapped off, they cause problems with use of the lane.

One of the primary benefits of gate equipment is that it is relatively cheap and often already available from former ACM lanes which are converted to ETC (or joint ACM/ETC lanes.) Gates may also be the only logical method if state laws prohibit the use of high-speed video camera enforcement.

Enforcement agents used to detect ETC violations come in a few varieties. First, a state trooper or equivalent law officer can be positioned at the toll plaza within sight of visual signals which indicate toll violators. Citations can then be issued at the location at the time of violation. Another option is to have law officers or officers of the toll authority monitoring high speed video equipment at the plaza, and issuing citations as they occur, either by witnessing them for the citation record, or by signaling mobile officers to stop violators and issue citations.

Enforcement agents and gates are used in states where the evidence laws prohibit the use of video data (owing to the ability to alter such evidence) or state law requires that the actual driver of the automobile be cited at the location of the violation, instead of citing the owner of the vehicle.

However, the most common and high tech form of enforcement is high speed video. These cameras are aligned to read license plates of offending vehicles as they pass through the toll

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[25] International Journal of Advanced Transport Infrastructure, *Above par on the Dulles Greenway*, Issue 3, November 1995, pp. 23-24.

plaza. The image of the vehicle, its license plate, and the location on the system are recorded on digital tape which is then later added to violation data from the lane controller to determine the citation to be issued. These systems are capable of detecting violations up to 100 MPH, (even if the ETC system works only to 40 or 50 MPH.) However, it should be noted that the computers controlling enforcement must be closely guarded and secure in accordance with state laws for use of such evidence for prosecution.

There are several types of violations that may fall under the enforcement category. Those which involve customers who's accounts have sufficient funds, but nevertheless are recorded as a violation must be processed out of the "citation" section of enforcement and into the de-bugging side. These types of violations can occur if the tag is improperly installed, is malfunctioning, has not been installed, or the ETC system is not working appropriately. There are a surprising number of this type of violations on systems throughout the United States, due mostly to missing or incorrectly installed tags. Another type of violation would be passing through the toll booth with a tag which is not valid. These may be patrons with insufficient funds, which then must be contacted for the payments and possible extra charges. Others may have possession of a stolen tag which then must be turned over to the police for prosecution. A third type of violation is a vehicle which has no tag, but is using an ETC-only lane. This type of toll evasion is perhaps the most important to catch since it could have the worst effect on revenue.

3.5.2 Privacy and Security

Privacy and security are major issues with Electronic Toll Collection. Since ETC systems can record transaction time, place, direction, and for closed systems, the entrance and exit points, privacy is obviously a major issue. Many concerns have been raised that tagging vehicles (either for ETC or traffic management and speed recording vehicles called "probes") is an invasion of privacy and these records can be used against patrons. Thus, it is necessary that individual toll records be highly safe-guarded to avoid such misuse of this data. (Also, the

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[26] NCHRP Synthesis 194, pg. 14.

recording of credit card numbers and bank accounts must also be protected for obvious reasons.) Systems and architectures of secure passwords and levels of access need to be built into the ETC system. Since networks of plazas are spread over large distances, this security must also be maintained over these large distances. Fortunately, today's computer technology sophistication makes security fairly easy, when procedures are followed.

Another consideration in this area is the Electronic Communications Privacy Act of 1986 which protects wire or electronic communications from illegal interception by unauthorized third parties.[27] Some protection is provided by this law. However, like all telephone records, ETC transactions can be required to be released for court proceedings. Despite protections, some patrons are still concerned about the use of transaction data. It must be stressed that use of the toll facility is usually a voluntary action, with a parallel free facility available. In addition, on most toll facilities with ETC, using ETC is optional. (Note, SR91 in California is an exception. All vehicles must be equipped with ETC tags on this facility.)

Finally, it is possible to offer anonymous accounts where no record of the owner of the vehicle is attached to the account. These types of systems are similar to today's prepaid calling cards in function. Obviously, this type of account must be paid for in cash and replenished in cash at the tag store, not through the mail. It is rare that this option is offered to users of ETC equipped facilities due to the other protections and options mentioned above.

3.6 Market Penetration and Marketing

Market penetration of ETC is a very important design consideration for the success of ETC systems. This is due primarily to the fact that a relatively high level of ETC use has been found to be necessary to outweigh the costs of the system. Most systems experience 10% to 35% market share. If not enough patrons use the system, the per-transaction cost for the users who do will be exceptionally high, outweighing any cost savings gained from the system.

[27] ibid, pg. 31.

Market penetration has been studied with relation to travel demand characteristics, such as purpose of trip and number of trips per week. It also has been related to vehicle class, implementation strategy, discounts and fees, payment options, and ease of use factors,

By far the most important factor in market penetration is travel demand characteristics. Typically, an attitudinal survey of patrons' interest in ETC is conducted to try and estimate ETC market. Often, this information is combined with travel demand survey information to calibrate the attitudinal model since it has been found that ETC surveys are answered by those favoring ETC more often than those who do not, giving biased results. Attitudinal surveys ask about use of ETC based on trip purpose, trip frequency, type of vehicle, implementation strategies, and deposits/fees.

Also, information from surveys and other systems is important in the design and implementation of ETC systems since initial design and implementation affects the success of the system. Survey information for ETC market demand can be used to properly determine lane mix at different plazas along a toll facility.

Results of surveys for trip purpose and trip frequency are shown in Figures 3.4 and 3.5. It is obvious by examining this stated preference data that those commuting to work and who use the facility several times a week are more likely to use ETC than others. This indicates that facilities which have a high rate of commuter usage are more likely candidates for successful ETC application. Although individual facilities will need to conduct surveys for each facility to determine the trip profile, these graphs indicate some generalizations for toll facilities in the United States.

Figure 3.4: ETC Use by Trip Purpose

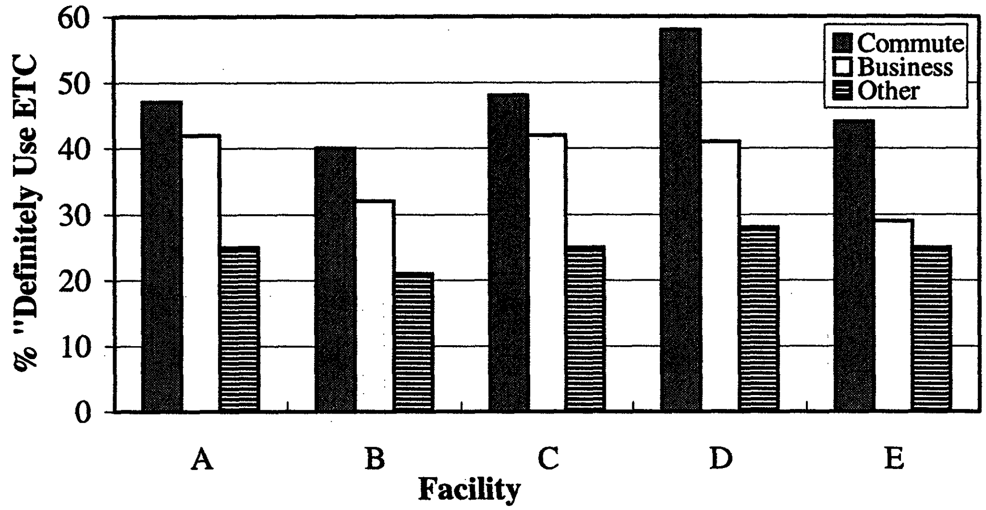
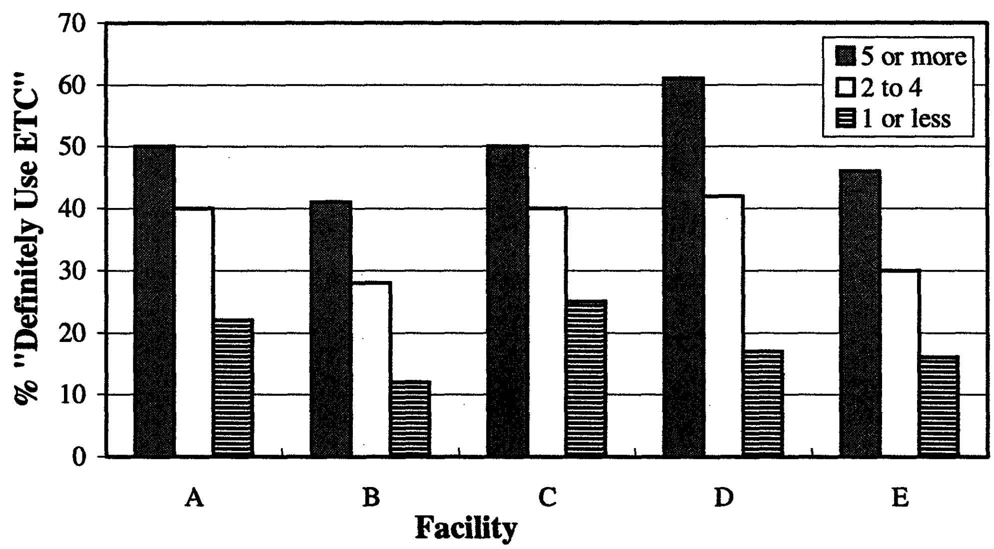


Figure 3.5: ETC Use by Trip Frequency



Sources: An ETTM Primer for Transportation and Toll Officials, ITS America, March 1995, pg. 46-47.
P. Marcella & D. Boss, Evaluating Market Demand, 1995 IBTTA International ETTM Symposium, pg. 56-57.

The relationship with trip purpose and frequency is likely related to the benefits versus the "costs" of using ETC to the user. A person making an infrequent trip, or a trip where they do not have to be to a certain place on time is likely to not want to go through the extra effort of obtaining a tag and using the system. Conversely, those who want to save time and find stopping for tolls every day inconvenient will find obtaining an ETC tag worth the benefits accrued over time.

Another relationship often studied is that of class of vehicle with respect to ETC usage. Table 3.10 shows this relationship for two systems. This indicates, along with other information, that depth of ETC use is not related to vehicle type. Indeed, the benefits to trucking companies who must maintain toll records for a huge number of transactions and reimbursement to drivers were the first vehicles to use ETC on a regular basis. Hence, the benefits to commuters are about equal with benefits to trucking fleets and other commercial operators.

Table 3.10

ETC Participation by Vehicle Type

	Percent Definitely use ETC	
Vehicle Type	Facility A	Facility B
Passenger Car	39%	49%
Commercial Vehicle	39%	43%

Source: P. Marcella & D. Boss, Evaluating Market Demand, 1995 IBTTA International ETTM Symposium, pg. 56-57.

Another important factor in ETC market surveys is the effect of implementation strategy on ETC market penetration. In general, if ETC is implemented only at one toll plaza, market for ETC will be relatively low. Various stages higher than just one plaza can also be examined, such as all mainline plazas, mainline and ramp plazas, and dedicated/bypass ETC lanes. Table 3.11 shows survey results of this type for four systems.

Table 3.11
ETC Participation by Implementation Strategy

	Percent Definitely use ETC			Percent Probably or Definitely use ETC
	Facility A	Facility B	Facility C	Facility D
Only at Current Plaza	18%	--	--	38%
At all Mainline Plazas	28%	--	--	61%
At all Mainline and Ramp Plazas	39%	35%	48%	72%
Dedicated and/or Express bypass lanes	52%	50%	58%	80%

Sources: *An ETTM Primer for Transportation and Toll Officials*, ITS America, March 1995, pg. 49.
P. Marcella & D. Boss, "Evaluating Market Demand", *1995 IBTTA International ETTM Symposium*, pg. 62.

Another consideration in ETC market penetration is the amount of deposit or purchase fee required to get an ETC tag. On most systems, this deposit is returned if the tag is sent back to the authority upon closure of the account. (As mentioned, the deposit is designed to keep the capital costs of obtaining tags low by encouraging returns.) However, there is a notable drop in survey respondents who said they would use an ETC tag if there was a $20-$30 deposit. Indeed, a survey for the Massachusetts Turnpike concluded that a drop from 45% "definite usage" to 29% given this level of fee.[28] Similarly, for a survey on the Illinois State Tollway, 50% of the respondents indicated they would be willing to pay $20 to $35 for the purchase (not a deposit) of an ETC tag. However, this number dropped to 12% of respondents for a $35-$50, and 4% for a tag cost of $50 to $65.[29] In some cases, such as the Oklahoma Turnpike, the initial tag is provided free upon opening an ETC account. Later tag replacements for lost or stolen tags are charged at a standard rate. Participation rates are often higher for this type of tag fee arrangement.

[28] Paul M. Marcella and David A. Boss, "Evaluating Market Demand", *1995 IBTTA International ETTM Symposium*, pp. 58-59.
[29] NCHRP Synthesis 194, pg. 29.

Perhaps as important as traffic mix and travel demand, surcharges and discounts on ETC transactions exert a strong influence on ETC participation. For instance, in the case of Dallas, in addition to a monthly fee, a per transaction surcharge of $.05 is added to ETC transactions.[30] Most systems offer no discount due to the problems of getting bonding approval. For example, E-470 in Denver with 33% ETC market penetration has no discounts or extra fees.[31] Other systems, such as the Lake Pontchartrain Causeway near New Orleans with 80% ETC use and the Tappan Zee Bridge in New York with 75% ETC use in peak hours offer 50% toll discounts for their systems.[32] Hence, it is easy to see that toll fees are very important in influencing market share.

As mentioned in Section 3.4.5, post-payment would seem to be preferred by ETC patrons, and pre-payment by toll authorities. However, most systems utilize pre-payment and those offering a post payment option rarely find patrons who desire the option. Hence pre- or post-payment does not seem to influence ETC participation rates. Notably, however, type of payment allowed is important. Credit cards, cash, and checks are considered to be standard for the industry. Systems with credit card only payment have seen some problems obtaining desired penetration rates.

Finally, other factors play a role in the market penetration of ETC systems. Certainly initial marketing is a key to greater starting participation rates. However, once a patron has opened an ETC account or examines others who have, the benefits of use must be clearly visible. (For instance, on the Williams Tunnel, part of the Massachusetts Turnpike, commercial van operators who do not have ETC accounts notice competitors who speed through dedicated ETC lanes while they wait in manual payment queues.)[33] Those who have a "wait and see" attitude about obtaining an ETC account will not be likely to convert if benefits are not clear at the start up of the ETC system. Hence good startup practices are very important. Other factors, such as acquisition and installation of tags, account replenishment, and problem

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[30] ITS America, *An ETTM Primer for Transportation and Toll Officials*, March 1995, pg. 48.
[31] See E470 Public Highway Authority Survey Response, Chapter 4.
[32] NCHRP Synthesis 194, pg. 12. and Marcella, pg. 63.
[33] Conversation with Massachusetts Turnpike Officials, January, 1996.

resolution must be easy for the patron at startup time, and continue into the future of the ETC program for better ETC penetration rates.

Fortunately, it has been the experience of most ETC systems that market penetration increases steadily, although sometimes slowly, as the system is in existence for more years. Although this is sometimes due to improvements in the system, such as adding more plazas or better technology, it is often due to familiarity of the system and continued increases in traffic flow. In addition, few who enter ETC programs return to regular payment methods. There is very low turnover. As the demand for ETC increases, the system must be designed to change with the demand to meet the needs of the growing ETC market.

In addition to the issues above, other issues in marketing play an important role in success of ETC systems. Professional logos, high visibility tag stores, well designed documents, press releases, and demonstrations are all important to put the ETC system in the public eye and keep it there. These must also be accounted for in the design and implementation of an ETC system.

3.7 Evaluation and Testing

Obviously, once an ETC system is put into place, the toll authority will want to evaluate and test the system. The primary purpose of this is to get the "glitches" out of the system and to make sure the contractor is living up to the agreements in the procurement documents.

Tests should be performed for calibration of equipment well before the opening of the system, or any newly added modifications. Unfortunately, no national standard for testing exists. Tests that have been conducted were frequently done on a controlled basis at individual agencies. They are often designed to evaluate a particular concern of the agency, and results are not comparable for different systems. In addition, testing is often proprietary as it involves the technical performance of system hardware. As ETC evolves, it is likely that national standards for testing will be developed and comparable data can be gathered.

Evaluation of ETC systems is even less defined than testing of equipment. Several different reports are available on the system characteristics and some performance parameters of existing systems. However, reports usually follow one or two particular toll facilities, evaluating individual systems. Unfortunately, no national consolidation of system evaluation and surveys exists for all systems. Toll authorities wishing to receive such information for use in designing and evaluating their own system must conduct their own surveys and collect individual papers. Often, key information is missing from each system which is important to evaluation. Thus, the task of evaluation is very difficult.

Some parameters which are reviewed in evaluation are given below:

- ETC participation rate (as a percentage of average daily transactions or ADT)
- Traffic flow before and after implementation of ETC system or upgrading of ETC system, such as adding dedicated ETC lanes to a mixed ETC lane only facility
- Change in ADT for manual and automatic coin lanes
- Number of errors as a percentage of accounts active that are attributable to hardware and software errors (i.e. not human)
- Typical causes of errors (e.g. incorrect mounting)
- Problems with equipment contractors
- Changes in waiting time for ETC patrons and non-ETC patrons
- Changes in per transaction costs for toll collection
- Overall perception of system by user

Fortunately, some researchers in the field have realized the need for standardizing evaluation criteria. In a major effort, T. H. Woo and L. A. Hoel undertook the task of forming a method to describe level of service at toll plazas. Noting that the traditional text on roadway capacity, the *Highway Capacity Manual* (HCM) contains no references to toll plaza design and level of service evaluation, they published *Toll Plaza Capacity and Level of Service*.[34] In this paper they describe an analysis method and establish level of service descriptions similar to those of the HCM. Although their work was developed on a non-ETC facility, it is directly applicable to the evaluation of ETC equipped plazas.

A set of test protocols for testing reliability has been suggested by W. Zhang and others.[35] They suggest that tests be broken into three stages:

1) Static/controlled tests under laboratory environment

   -time domain measurements to test communications speed

   -interference tests using other sources of RF interference (for RF systems)

   -measurements of communications range

   -environmental test to evaluate reliability under harsh weather conditions

   -electro-static discharge test to determine reliability of electronic components

2) Functionality tests

   -transaction tests to verify if proper transaction information is recorded on equipment

   -fraud or cheating tests to evaluate enforcement and potential loopholes

3) Long Term Tests

   -designed to test operational reliability of the system in actual toll collection operations

   -requires sample sizes large enough to determine statistics accurately

3.8 Chapter Summary

This chapter has provided a formal introduction to Electronic Toll Collection from a consolidation of information available in the field. The types of ETC systems and

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[34] T.H. Woo and L.A. Hoel, "Toll Plaza Capacity and Level of Service," *Transportation Research Record*, issue 1320, pp.119-127.

[35] Wen Zhang, et al, *A Primer on Electronic Toll Collection Technologies*, Transportation Research Board, 74th Annual Meeting, January, 1995, Washington DC, pp 14-17. A detailed description can be found in W.

technologies used for communications were covered first. There are currently many configurations available but radio-frequency read-only and read-write systems are most common. Next, system design considerations were explained. Items covered include: architecture and components of an ETC system; accuracy and reliability of electronic toll collection; health and safety considerations with regard to electromagnetic waves produced by ETC equipment and non-stop traffic through toll plazas; traffic operations at the toll plaza including lane configurations, demand levels, and channelization; service and maintenance issues; and accounting and tag distribution processes which are not part of traditional toll collection methods. Then, institutional issues, such as goals which an authority has in mind when ETC is selected, the cost of such ETC systems and capital outlays involved, and the type of ownership arrangements authorities might choose with regard to ETC equipment. Patron payment was covered from the perspective of type of payment which can be used (cash, check, credit card, etc.) and when payment is made, either before tolling or after tolling, and the plusses and minuses of each addressed. Interagency issues, such as individual tags being available for use on multiple ETC systems and avoiding duplication were covered only lightly. Such issues are very complex and some references were provided for further study. The next three topics: enforcement, privacy, and security were addressed since they are a vital concern among toll agencies and patrons. Enforcement is one of the problems with ETC systems as will be seen in the case studies in Chapter 4. The next part of the introduction to ETC included market penetration and marketing issues. These were brought forward since they may help an agency achieve better ETC penetration rates. Finally, evaluation and testing of ETC systems, both at startup and in monitoring phases was summarized. However, as is mentioned later, better evaluation techniques are needed.

Zhang, L.N. Spasovic, E. Niver, *Radio Frequency (RF) Tag – IC Card Based Electronic Toll Collection (ETC) System Test Plan*, Institute for Transportation, New Jersey Institute of Technology, April 1994.

Chapter 4

Case Studies

The purpose of this chapter is to outline the case studies performed for this research. First, the information collection technique in the form of a survey is presented. Then, information from each of the respondents is presented, along with interpretations of the information. Finally, a group of general lessons learned is drawn from the case studies.

4.1 Electronic Toll Collection Survey Design

When research started on this project, information for U.S. facilities using Electronic Toll Collection (ETC) was limited to reports from the International Bridge, Tunnel, & Turnpike Association (IBTTA) and the Transportation Research Board (TRB). Other information in the form of short articles was available on a system by system basis. However, no large scale, detailed summary existed for a major proportion U.S. toll facilities using ETC. From the information that was available and the design considerations presented thus far, a survey was generated which was sent to a targeted group of ETC-equipped toll authorities in the United States. (See Section 4.2 for case study selection criteria.)

The purpose of the survey was to collect the most relevant and salient information about each case study as determined by the author from studying information presented in Chapter 3 and related sources. The following is a summary of information asked for in the survey. (Please see Appendix A for an actual copy of the survey and responses.)

- General Facilities Information
  - Type of facilities (bridge, causeway, commuter roadway, etc.)
  - Length of facilities (in miles)
  - Number of average daily transactions

- Type of toll system (barrier/open or ticket/closed)
- Number of toll plazas total
- Number of ETC equipped plazas
- Range of tolls on facilities

This section was designed to ascertain location of system, type of facility, levels of use, levels of ETC use, and levels of tolls, which are important in providing a benchmark from which to compare respondents

- Facilities Wide Toll Lane Configuration
  - total of each type of toll lane - manual collection lanes, automatic coin collection lanes (ACM), dedicated ETC lanes, and mixed ETC/ACM lanes

This section was designed to update information already obtained from other sources and to provide level of implementation information for each respondent.

- Electronic Toll Collection System
  - Current use of ETC
  - System name, vendor
  - Technology of system, type of system (read only, read/write, etc.)
  - Date ETC opened
  - Number of ETC transactions as percent of total, also by class of vehicle
  - Number of ETC tags in circulation
  - Enforcement system
  - Pre-pay or post-pay
  - Toll discounts or fees, tag deposits, minimum balance of pre-paid tolls
  - Payment methods
  - Availability of anonymous tags
  - Operation of tag office and accounting, installation requirements

This section was designed to get pertinent information about type of ETC systems in use, penetration of ETC market, and ETC characteristics to relate system success with system parameters.

- Most Used or Congested Toll Plaza With ETC
  - Name of plaza
  - Location (rural, suburban, urban)
  - Toll lane configuration for most used plaza
  - Peak hour demand
  - Depth of ETC penetration at this plaza

This section was designed to summarize information for the bottleneck of most systems - the most used (or only) toll plaza - and to look at the benefits/problems of ETC associated with such plazas. The most used or congested plaza with ETC was usually defined as the plaza with the greatest average daily transactions where ETC is in use. Note that toll authorities with only one plaza will not have a response for this section.

- System Evaluation
  - Authority motivation for ETC system installation and use
  - Authority's opinion of whether the benefits of the ETC system have exceeded its cost
  - Special techniques for increasing toll processing speed
  - Cost of retro-fitting for ETC including civil construction
  - ETC equipment ownership and operation
  - Public perception of ETC program
  - Problems with tag technology
  - Speed restrictions at ETC lanes
  - Enforcement problems
  - Channelization / safety problems
  - Changes in motorist average delay since ETC implementation
  - Off peak changes since ETC implementation
  - Changes in queues since ETC implementation
  - Time based pricing considerations, congestion pricing
  - Has congestion on facility around ETC plazas decreased or increased
  - Additional comments

This section was designed to get common information about successes and problems associated with ETC systems for each respondent. The answers are more qualitative and provide more information than previously available surveys.

The problem with asking evaluation questions is, of course, that no standards of evaluation exist, as noted in Chapter 3. However, specific questions were geared so as to ascertain the authority's view of ETC without getting into a specific evaluation. For instance, "Have the benefits of the ETC system excluded the costs?", answered with a yes or no, will indicate whether or not the authority feels the benefits have exceeded the costs of the ETC system. In this manner, non-quantifiable information, such as possible increased public acceptance of tolling due to ETC, as well as quantifiable information, such as possible decreased operations costs, can be evaluated with one question, not getting into the technique used to analyze such information. As noted in Chapter 3, there is a real need to develop such a standardized evaluation and benchmarking program in the toll collection business.

4.2 Selection of Case Studies

Case studies were selected on several criteria. First of all, since this research was primarily funded for studies of Puerto Rico's toll expressway system which currently does not use ETC, systems which use retro-fitted ETC were primarily selected since the results would be more applicable to Puerto Rico. (Although non-retro-fitted cases are included.)

Secondly, U.S. systems only were selected for three reasons:

1) Information on systems and surveys is in English
2) Driving characteristics and willingness to pay tolls for road use are different around the globe but U.S. systems generally share the same characteristics. Non-U.S. systems (with the exception of perhaps Canada) most likely have differing demand and patron characteristics that will affect ETC system success characteristics.
3) It is intended that this research will produce analysis techniques and base line information for use by other U.S. toll authorities, but in particular for Puerto Rico.

Also, only major systems for which at least some information was available from outside sources, such as the IBTTA, before the survey were selected to increase the chances of getting good results. Although this seems to bias the information obtained, since the number of case studies involved is fairly low, the analysis will be from a qualitative standpoint.

4.3 Analysis of Case Studies

Each case study is analyzed in five different ways: general characteristics, toll lane configuration, ETC system characteristics, most congested plaza (if available), and qualitative features. The reasoning for each of these is given below.

First, the general characteristics of the facility or facilities operated by the toll authority are listed: type of facilities, length of facilities, average daily transactions, toll configuration, number of toll plazas and ETC equipped plazas, average miles between plazas, and toll rates. The type of facility is important because rural tollways are less likely to have daily repeat customers (considered an important aspect for high ETC penetration - see Chapter 3) than commuter roadways and metropolitan bridges. The length of facility and average daily transactions are important to determine the size of the facility. Large facilities may have a difficult time implementing ETC due to the number of ETC toll lanes which must be made available and the cost of equipping a large number of patrons with accounts and tags. Also, total length can be used to determine important ratios such as average miles between plazas. If plazas are close together and of the barrier type, then patrons may gain more benefits from an ETC program since they will not be stopping to pay tolls frequently. Conversely, those systems with few plazas which are far apart have less to gain from ETC since patrons do not stop as often to pay tolls. The number of ETC equipped plazas as a proportion of all plazas is important since many have indicated they will be more likely to use ETC if it is installed at all plazas. (See Table 3.11.)

Average daily transactions (ADT) can be used to determine the ratio of ETC tags to ADT and then compare this ratio to the ETC market penetration rate. If the ratios are similar, then each ETC tag is used daily on average. An ETC to ADT ratio which is much higher than the ETC market penetration likely indicates tags are used less than daily, and may indicate a higher cost ETC system. (Tags are typically paid for by the toll authority.)

The type of toll configuration will most certainly affect the type of technology used. Read-only systems cannot be used on closed toll configurations as explained earlier. Also, for closed systems, the patron generally needs to stop at just two toll plazas per trip. On open systems, the patron may need to pay tolls at several plazas, and all traffic is stopped at mainline barrier plazas. Again, the argument can be made that the greater the number of stops under traditional toll payment methods, the more likely ETC will be a successful due to the change in the number of stops required. The number of toll plazas and average miles between plazas has already been explained above.

Toll rates are important from a cost standpoint. If rates are low enough to use automatic coin machines (ACM), then faster processing rates and lower costs of collection (as opposed to systems with only manual collection) were probably the norm on the facility before the application of ETC. Thus, introduction of ETC may not be cost effective, and will not add as much plaza capacity as might be expected, as noted in Chapter 3.

In the second section of each case study, the toll lane configuration is examined. The number of ACM lanes is important for reasons described above. The number of ETC lanes available as part of the whole is important just like the number of ETC equipped plazas as part of the whole. With few ETC lanes available, patrons may be less inclined to use ETC, especially if dedicated ETC lanes are not available. Also, the ETC program may have a visibility problem if only a few lanes at a few plazas are equipped with ETC. It may look like an experiment to customers or just a convenience item rather than an important toll collection option with many benefits.

ETC system characteristics are presented next: ETC market penetration, ETC tags in circulation, toll discount/fee, tag deposit, minimum balance, payment methods, and installation. Several of these items were covered in Chapter 3.

ETC market penetration is often considered to be the number one success characteristics of ETC programs. (It is the most highly quoted figure for all ETC systems.) This may be an inappropriate measure of success for ETC systems, since high ETC penetration rates can be achieved through discounting tolls which may hurt revenue streams. A more appropriate measure may be the per transaction cost of each type of toll payment as a percentage of toll collected, for instance. Nevertheless, ETC market penetration will be used as the most important characteristic along with other characteristics since it appears to be the most important to toll authorities at the time of writing.

The number of ETC tags in circulation is important, as mentioned above, because the ratio of tags to daily transactions can determine how often the tags are used on average. Toll discount or extra fee is important since it can greatly affect the depth of ETC penetration, as has been discussed several times. It can also affect revenue stream since less toll is collected. Tag deposit, to a lesser extent, can also affect ETC participation because high tag deposits make it harder for the average patron to join the ETC program. Minimum balance is almost exactly parallel to tag deposit in terms of effecting participation rates.

The payment of tolls is important, either pre-pay or post-pay, since pre-pay tolls are often time banked so the authority can earn money on the amount of deposits before they are used to pay tolls. Also, payment methods can affect ETC usage and patron convenience. By allowing only credit card payment for ETC, for instance, those who can not get credit cards cannot participate in the program. Finally, installation can be an important factor especially for large systems. If professional installation is required and only one location exists for installation, it may be very inconvenient for the patron to drive to the installation facility at a specific time to get the ETC tag installed. Conversely, those systems where users install tags can send tags to patrons through the mail, and thus save on professional installation costs as well as increase patron convenience.

For facilities with more than one plaza, the characteristics of the most congested plaza (defined usually as the ETC-equipped plaza with the greatest number of average daily transactions) are presented: lane configuration, peak hour demand, and depth of ETC participation at the plaza. Most often the highly congested plaza is the starting point for ETC and ETC will probably reap the most benefits at such a plaza. This is because these plazas are the most likely to need expansion, are located close to a city's core, and are most frequented by commuters. The number of ETC lanes to total lanes may be higher at such a plaza, as well as ETC participation rates. In addition, knowing the lane configuration allows one to perform a simple capacity analysis and make a comparison to peak hour demand.

The qualitative issues discussed are primarily related to the toll authority's goals, costs and benefits, operational problems (congestion, tag failures, enforcement), patron views, waiting times and queue lengths.

The toll authority's goals are very important to determine whether or not the ETC system is successful, as mentioned previously. For instance, if the goal of installing an ETC system was to provide another payment method, the cost effectiveness of the system is important. On the other hand, if the goal was to increase capacity of the current plaza without expansion by using ETC toll lanes, the depth of ETC penetration is more important.

The costs and benefits of an ETC system are not specifically requested in the survey. Instead, the question asks, "Have the benefits to your authority or organization exceeded the cost of the ETC system/program?" This provides an immediate answer to the question of whether or not an ETC system is considered successful by the toll authority, because presumably any organization will have as its goals benefits exceeding costs. It also helps to evaluate non-quantifiable benefits such as patron satisfaction and toll authority image, as noted earlier.

Operational problems and considerations, addressed next, include tag reading reliability, speed restrictions, enforcement, channelization and accidents, and congestion points. Tag reading reliability is one of the major concerns of most toll authorities since it causes the greatest number of direct headaches. Systems which fail frequently cost the authority in lost time trying to fix problems, in lost revenue, and in negative publicity about the ETC system. Speed restrictions are important only from the prospect that non-stop ETC lanes may be considered not all that more convenient if speeds are restricted to less than 10 mph. Enforcement is a major issue with all toll authorities. Concern has been raised about the number of toll evaders that might try to use ETC lanes and the difficulty in issuing citations to evaders. Obviously, not being able to enforce toll collection results in a loss of revenue. Channelization and accidents are important since safety is also a major issue with many toll authorities. Finally, congestion points are another key concern which is not often addressed in ETC literature. Increasing flow through a toll plaza may not be appropriate since downstream interchanges or roadway may not be able to handle the increased traffic, causing greater total backups than just the plaza and the downstream congestion point put together.

Patron's views are important since customer satisfaction is a prominent business practice in today's society. A disliked ETC system could be seen as more reasons for the public to push for elimination of tolls altogether. Also, the privacy question with regard to use of ETC transaction records is important since if privacy is questioned, fewer patrons may be inclined to use the system.

Finally, waiting times and queue lengths are another measures of success of an ETC system, especially if reducing these level of service characteristics was part of the toll authority's goals in implementing an ETC program. Also, these characteristics are one of the most touted benefits of ETC systems.

Many of these issues are addressed for each case study below. Then, an entire summary of generalized observations from the case studies is made.

4.4 Illinois State Toll Highway Authority (ISTHA)

Facilities: Tri-State, Northwest, North-South, and East-West Tollways

Type of Facilities:	Commuter Beltway - urban
Length of Facilities:	276 miles
Average Daily Transactions:	1.2 Million
Toll Configuration:	Barrier
Toll Plazas:	57
ETC Equipped Plazas:	15
Miles Between Plazas (ave.)	4.8 miles
Toll Rates:	$.25 - $.95 for autos

The Illinois State Toll Highway Authority (ISTHA) operates four tollways in the Chicago Metropolitan Area. The vital statistics given above indicate that this is a rather large set of facilities. Note that the average distance between plazas is fairly large for an urban system (around 5 miles.) The fact that this system is a barrier system, has many commuters, and has many plazas all indicate that this system is likely to be a successful candidate for ETC usage, according to the design principals discussed previously. In addition, the low toll rates also make it a good candidate for automatic coin collection (ACM), indicating that a low cost toll collection method (ACM) may already be in place, which could compete with ETC collection costs. The facilities wide configuration for ISTHA is:

Toll Lanes Total:	435
Manual:	181
Automatic Coin:	254
Mixed Manual/ETC:	61
Dedicated ETC:	4
Mixed Automatic Coin / ETC:	106

One point of note: In many of the case studies, such as this one, the total number of lanes is far smaller than the sum of the types of lanes given. This is primarily due to the existence of multi-use lanes which are often counted multiple times (e.g. 4 manual and 4 manual/ETC lanes), or are reversible, being one physical lane with two or more types of collection, or are double lanes, for peak loading, utilizing two toll collection booths on the same lane in the same direction.

There is a large occurrence of ACM lanes on these facilities (about 60% of the total.) This probably indicates that toll collection costs are low on average and collection by ETC may be more expensive than previously used methods. There is a low number of ETC lanes out of the total, about 15%. In addition, only 26% of the toll plazas are equipped with ETC systems. Thus, a low market penetration is likely on this system. Key information about the ETC system is as follows:

ETC Market Penetration:	1%
ETC Tags in Circulation:	14,000
Toll Discount / Fee:	none
Tag Deposit:	$38 auto
Minimum Balance:	equal to next toll
Payment:	cash, check
Installation:	by user

This information shows a low usage rate for ETC, but it is consistent with the number of tags in circulation. (More precisely, if each ETC tag is used once a day on average, 14,000 ETC tags divided by 1.2 Million transactions per day equals 1.2%, roughly the ETC market penetration rate. This indicates that tags are used frequently.) The market penetration rate seems to indicate that the ETC program has not been very successful. This is most likely due to a low number of plazas being equipped with ETC and the low number of ETC lanes as a fraction of the total, as noted earlier. However, considering the size of these facilities and total daily transactions, implementing a full scale ETC system will take a long time and more investment, as indicated below. Other factors affecting ETC penetration to note are a fairly high tag deposit ($38 for autos) compared to other systems, and the lack of credit cards as a payment method, both of which can contribute to lower penetration rates. However, note that the minimum balance is very low, just equal to the next possible toll, which can lead to higher penetration rates.

ISTHA indicated the I-Pass program uses read/write technology. However, the write capability is probably unused since this is a barrier type facility. Nevertheless it is important to mention since the use of read/write technology is increasing, as indicated in the conclusions for this chapter.

Some information on the most congested plaza which utilizes ETC is given below:

Total Lanes:	20	
Mixed ETC/Manual Lanes:	10	
Mixed ETC/ACM Lanes:	10	
Lanes ETC dedicated/express:	none	
Peak Hour Demand:	7-8 AM	11,400 vehicles/hour
ETC Market at plaza:	6%	

For this crowded plaza, there is a better proportion of ETC lanes than the rest of the system, with 100% availability, although no dedicated ETC lanes exist. From the information presented in section 3.3.4, the peak hour demand indicates that this plaza is a likely candidate for a dedicated ETC lane; therefore a dedicated lane may be appropriate here, but none exist at the time of survey. Also, the peak hour demand does coincide with the morning commuting peak, which indicates that the likelihood of repeat users is high.

With regard to traffic operations, the ISTHA system occasionally experiences backups into plazas due to downstream congestion. Some critics of ETC systems have indicated that this situation could worsen once ETC is installed given the increased throughput of ETC systems, as noted earlier. However, ETC usage has not worsened the backup situation, according to the authority.

ISTHA indicates the reason for installing an ETC system is for patron convenience. This may be some of the cause for the smaller ETC installation level (fewer ETC equipped plazas) and subsequent low usage rates (as noted in Chapter 3.) In addition, ISTHA indicates that the costs to the authority have not been exceeded by the benefits obtained at the time of the survey, which may also affect the authority's future plans for full scale implementation. In addition, as will be detailed more in Chapter 7, systems which have a high frequency of automatic coin collection before the installation of ETC, as ISTHA does, often find ETC more expensive on a per transaction basis since automatic coin collection also saves labor costs but the accounting costs are lower than ETC systems.

There are enforcement problems with ISTHA's ETC system: "Electronic toll collection increases violations if video is not used as a deterrent and enforcement."[36] This is an important point to note, since enforcement and expected revenue is very important in the toll facility bonding process, and a major concern among many toll authorities. Enforcement can also tie into costs since a high level of enforcement costs more than a low level, and some states require expensive labor to be used for enforcement, such as state troopers, instead of lower cost video systems and a processing office.

On the positive side, ISTHA indicated that patrons like the ETC system. Also, although queue lengths and wait times have not changed appreciably, the installation of dedicated ETC lanes and an increasing market share should produce a noticeable decrease in waiting times and queue lengths.

This system is expanding, with a planned total investment of $46 Million, $16 Million of which has been spent so far. It is likely that the ISTHA system will become more successful in terms of market penetration in the future as new ETC lanes and dedicated ETC lanes are

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[36] *Electronic Toll Collection Survey, ISTHA Response*, May 1996, unpublished.

added, more plazas are ETC equipped, and familiarity with ETC systems increases across the region it serves.

Key points from Illinois State Toll Highway Authority:

- Large retro-fit systems with high average daily transactions and a high number of plazas take a long time and a large amount of money to develop ETC as a significant payment method, primarily due to the large amount of cost and time involved in equipping many plazas and lanes for ETC use.
- Equipping highly congested plazas with a high percentage of ETC lanes is recommendable, given the high penetration rates likely at these plazas. The most congested plaza on the ISTHA system has ETC equipment in every lane, and consequent ETC penetration rates are much higher than average.
- Enforcement is a difficult and ETC can increase violations if enforcement is not properly executed.
- Backups downstream from plazas do not appear to be worsened by installation of ETC systems. (However, the ETC participation rate is so low that significant increases in flow have probably not occurred.)
- Perhaps a more aggressive marketing campaign and high profile ETC system could help ETC participation rates at ETC equipped plazas.

4.5 E470 Public Highway Authority

Facility: E470 Public Highway (Denver)

Type of Facilities:	Commuter Beltway
Length of Facilities:	5.5 miles
Average Daily Transactions:	8000
Toll Configuration:	1 Barrier, 4 Ramp
Toll Plazas:	5
ETC Equipped Plazas:	5

Miles Between Plazas (ave.)	1.1 miles
Toll Rates:	$.50 for autos

The E470 Public Highway is a 5.5 mile connector built as an uncongested, high speed beltway and to provide the best access to the new Denver International Airport. The tollway was designed with ETC in mind. It is a relatively small facility, at just 5.5 miles in length. However, note that the density of plazas is fairly high (1.1 miles apart on average.) Being a barrier system, with some ramp barriers, having a high plaza density, and having some type of repeat business (employees and commercial traffic going to the airport, frequent flyers, etc.), this roadway is a good candidate for ETC. However, note that automatic coin collection could also be used here due to the low tolls. In addition, being primarily a connector to the airport, it seems that mostly commercial fleet vehicles (either freight or multi-passenger vehicles) or employees who frequent the airport would be interested in the ETC system since local travel to airports is relatively infrequent for everyday users.

The facilities wide toll lane configuration is:

Toll Lanes Total:	14
Manual:	2
Automatic Coin:	0
Mixed Manual/ETC:	8
Dedicated ETC:	0
Express ETC (~65 MPH)	4

Here we see a large percentage of ETC lanes of the total, about 86% and a 100% equipping of plazas, indicating a higher ETC penetration rate. Also note the existence of express ETC lanes, and the exceptionally high speeds allowed on these lanes. (The lanes will be moving to 70 MPH starting in June of 1996 according to ISTHA.) Although the traffic on the roadway does not seem to justify express ETC lanes, the facility was built with future demand in mind and to provide fastest access to the airport. Thus, a strong ETC system and express lanes are consistent with the purpose of the roadway in the future.

Key information about the ETC system is as follows:

ETC Market Penetration:	33%
ETC Tags in Circulation:	7364
Toll Discount / Fee:	none
Tag Deposit:	$25 auto
Minimum Balance:	$5
Payment:	cash, check, credit card
Installation:	by professional at tag store

This information shows an average penetration rate, when compared to other ETC systems surveyed and other sources. (General penetration rates range from 30% to 40% for systems which have been in place for some time and do not offer toll discounts for ETC use.) When comparing the ratio of ETC tags in circulation to average daily transactions, (i.e. 7364 tags / 8000 ADT = 92%) to the ETC penetration rate (33%), it can be seen that on average tags are only used about once every three days (33%/92%). This is most likely due to the infrequency of trips to the airport by most patrons. However, the ETC market penetration is good, as a fraction of the total, indicating a successful program when compared with other ETC systems, as noted. Other factors here which are noteworthy, include an average level tag deposit ($25 for autos) and a minimum balance which is fairly low at $5. Both of these favor a higher ETC penetration rate. However, professional installation is required, which may hurt the depth of ETC penetration.

Although no specific reason was cited by the authority for installation of ETC, the reasons for the ETC system is somewhat obvious: cost savings, convenience, lower equipment costs for new ETC lanes, public image, and other benefits listed in Chapter 3. Facilities like E470 are important studies as the number of new toll facilities being built increases. These facilities have shown the level of ETC integration that is possible on a new facility. (Similarly, the SR91 project in California also could be a study for new roadways.)

E470 is one of the few with an automatic vehicle classification system (typically used to make sure a lower class tag is not used on a higher class vehicle). This is useful to determine tolls and enforce ETC rules. Also, ETC participation rates have been increasing since the 1995 IBTTA survey. Given the nature of trips on the roadway (mostly to the airport) it is probable that getting a high percentage (~75%) of ETC market penetration will not be possible, unless use of the tags is connected to other daily activities such as parking fees or transit fares.

Key lessons from E470 Public Highway Authority

- Smaller systems are easier to install ETC on and get better ETC penetration rates (compared to ISTHA case study)
- Facilities designed with ETC in mind are likely to have a higher ETC participation rate from the beginning than older retro-fitted systems.
- The fraction of all tags used daily is directly tied to the nature of trips on the road. Since E470 is a connector to the airport, trips are not of a daily nature and tags see less use by airline passengers, but probably see greater use by commercial vehicles and employees.
- High speed ETC lanes are viable already today and can be used on a well designed facility. Perhaps retro-fitted facilities can someday utilize express ETC lanes.
- A high percentage of ETC equipped lanes and plazas can help ETC penetration rates, as is noted in other case studies.

4.6 Texas Turnpike Authority

Facility: Dallas North Tollway

Type of Facilities:	Commuter Roadway
Length of Facilities:	21 miles
Average Daily Transactions:	307,000
Toll Configuration:	Barrier
Toll Plazas:	3 Barrier, 20 Ramp
ETC Equipped Plazas:	all plazas
Miles Between Plazas (ave.):	.91 miles
Toll Rates:	$.25 - $.50 auto

The Texas Turnpike Authority runs the Dallas North Tollway, a 21 mile commuter roadway. The information above indicates that this is a medium sized facility. The average distance between plazas is very low, less than 1 mile. Since this is a barrier system with a large commuting patron base, and very close plaza spacing, it is a likely candidate for ETC. In addition, the frequent use of automatic coin collection on this facility is probably due to the fairly low tolls. The facility wide toll lane configuration is:

Toll Lanes Total:	88
Manual:	37
Automatic Coin:	45
Mixed Manual/ETC:	82
Dedicated ETC:	8

Note the large presence of automatic coin lanes. In addition, the number of ETC lanes to total lanes proportion is very high, and appears to be above 100% (90/88). However, this is probably due to double counting and reversible lanes as noted in the ISHTA case study. Regardless, the density indicates a high convenience rate for ETC patrons. Also, the number of ETC equipped plazas is 100%, promoting more ETC use. Key information about the ETC system includes:

ETC Market Penetration:	40%
ETC Tags in Circulation:	123,000
Toll Discount / Fee:	none
Tag Deposit:	$25
Minimum Balance:	$40
Payment:	cash, check, credit card

Clearly the Dallas North Tollway (DNT) has a successful ETC system. The 40% ETC penetration rate is similar to the other case studies and other facilities which do not offer a toll discount to ETC patrons. The fraction of ETC tags in circulation as part of the total daily transactions is about 40%, which corresponds closely to the ETC market penetration figure, indicating that tags are used on average once a day. The tag deposit is an average tag deposit (again, compared to other systems) and all forms of payment are accepted, again helping the ETC market share. Note that the minimum balance is fairly high, but that it does not seem to inhibit normal ETC penetration rates.

Of special note on the DNT is the most congested plaza data, as follows:

Total Lanes:	15	
Mixed ETC/Manual Lanes:	6	
Mixed ETC/ACM Lanes:	7	
Dedicated ETC:	2	
Peak Hour Demand:	7:00 - 9:00 AM	10,000 vehicles/hour
ETC Market at plaza:	42%	

Here we see a slightly higher ETC usage rate, probably due to the peak hour occurring during the morning commute, indicating patrons during this time are more likely to be daily patrons and hence use ETC, and the high probability that most patrons pass through this plaza, being the most used plaza on the facility. To a lesser extent the availability of ETC in all lanes may also help ETC use. In addition, dedicated ETC lanes exist, but are restricted to 10 mph for safety. These dedicated lanes may also contribute to ETC use since patrons with ETC will not have to wait in any lines or for patrons in front of them who are non-ETC users.

Since most of the lanes are available for traditional collection in addition to ETC, configuring the lane capacity for each type of lane to match the market shares for each type of payment is easier since lane configurations can be changed without adding extra equipment. (Although equipping every lane is expensive.) Taken to the extreme, if the market share changes significantly throughout the day or week, like daily trips being heavily ACM and ETC transactions and peak vacation periods being mostly manual with little ETC, lanes can be reconfigured without any hassle to match the two different types of peaks.

A quick capacity analysis of this plaza reveals some interesting facts. If the plaza, which has 15 lanes, was all automatic coin lanes (with 500 vph capacity each - see Chapter 5 for lane capacities by lane type), the capacity would be 7500 vph. However, since the plaza has an ETC system, the capacity is around 9700 vph, as shown in Table 4.1. Hence the inherent capacity increases available with ETC are obvious at this plaza. The demand during the peak hour is 10,000 vph. The ETC equipped plaza probably functions well with a capacity of 9700 vph and a demand of 10,000 vph. However, an ACM only plaza with capacity of 7500 vph would experience quite a bit of queuing for the same demand level.

The Texas Turnpike Authority (TTA) stated that reducing queuing at barrier plazas was the motivation for installing ETC. Although traffic has increased system wide by 79% since ETC was installed, delays have not worsened, and queues are shorter. Presumably, this is due to an ever increasing market penetration of ETC, giving increased capacity at plazas without expanding them, matching the increase in demand. This indicates that the TTA has fulfilled its goals for the ETC system. In addition, the TTA stated the benefits of the ETC program have exceeded the cost of the program, which could be expected given the authority's motivation for the ETC system and the results so far.

Table 4.1
Theoretical Capacity of Barrier Plaza I of Dallas North Tollway

number/type of lane	capacity per lane (vph)	total capacity (vph)
6 manual lanes	400	2400
7 ETC/ACM mixed lanes	700	4900
2 Dedicated ETC lanes	1200	2400
Total Capacity		9700

Key Lessons from the Texas Turnpike Authority

- Despite traffic increases by 80% since ETC installation, queues have remained the same
- A high minimum balance may not hurt ETC participation (high minimum balance was cited at the beginning of the chapter as a deterrent to high ETC penetration rates)
- Capacity at congested plazas can be increased using ETC when demand outstrips traditional collection methods.
- Dedicated ETC lanes may encourage ETC use.

4.7 Port Authority of New York and New Jersey

Facility: Lincoln Tunnel (New York City)

Type of Facilities:	Commuter Tunnel
Length of Facilities:	1.5 miles
Average Daily Transactions:	56,000 total, 5200 busses
Toll Configuration:	Barrier
Toll Plazas:	1
Toll Rates:	$.4.00 auto, $3.00 bus, $4.00/axle trucks

The Lincoln Tunnel is one of the main points of crossing into New York City. Currently, The Port Authority of New York and New Jersey (PANYNJ) operates a 2.5 miles exclusive bus lane during the morning peak hour (6:30-10:00 AM) providing a direct route to the tunnel, avoiding regular traffic, and significantly reducing travel time. Busses using this lane are also permitted to use an exclusive ETC lane, if they have an ETC account. ETC for regular patrons is currently in the planning stages.

The toll lane configuration for the tunnel and ETC details include:

Toll Lanes Total:	14
Toll Lanes Manual:	13
Toll Lanes ETC:	1
ETC Market Penetration:	3% of total - 30% of busses
ETC Tags in Circulation:	3500
Toll Discount/Fee:	10% discount
Tag Deposit:	free at startup, now $60
Minimum Balance:	2 months of tolls
Payment:	check
Installation:	user

Although only one ETC lane is offered, it is used by a large percentage of the busses. (ETC is not available to all traffic through the tunnel at the time of the survey.) Thirty percent penetration rate for the available market (busses) is about average compared to other case studies and other sources, such as ETTM System Surveys conducted by the IBTTA.[37] Note that the ETC penetration rate is lower than the ratio of tags to average daily transactions (3500 tags /5200 busses daily = 67%), indicating a somewhat low usage of tags available on a daily basis. This is likely due to busses being used on different routes each day, some of which do not use the tunnel.

[37] International Bridge, Tunnel, and Turnpike Association (IBTTA), *ETTM System Survey, March 1995.*

Although the initial fee of $60 and the high minimum balance may inhibit some patrons, it seems unlikely since most bus operators are large commercial enterprises for whom which these fees are not extraordinarily large.

The motivation that PANYNJ cites for installing ETC is to help the express bus lane. (After all, speeding down an exclusive bus lane only to wait in line to pay a toll could hurt the usage rates of the exclusive lane.) PANYNJ feel the benefits of the program have exceeded the costs. Time savings for busses using ETC have been great, with little noticeable improvement for regular patrons.

PANYNJ has experienced problems with ETC system, including water getting in externally mounted ETC tags. They have also experienced problems with non-ETC busses using the ETC lane. Even though video enforcement is used, they have had a hard time identifying non-ETC busses. In addition, keeping enrolled customer's accounts current has been a problem.

Overall, the ETC system for busses in the Lincoln Tunnel seems to be a success. Future installation of ETC for all patrons under the EZ-Pass program planned for the entire area will probably help reduce costs at this facility since toll collection now must be strictly manual due to the high toll on the tunnel. However, the tunnel is a key congestion point, and backups from the tunnel could extend into the plaza as plaza capacity increases.

Key Lessons from the Lincoln Tunnel:

- Exclusive transit lanes can speed transit times, hopefully increasing transit usage
- Bus and other commercial fleets are likely candidates for ETC usage (note 30% ETC penetration rate in this case study)
- External tags may deteriorate due to weather
- Enforcement can be difficult for ETC equipped lanes, even with video enforcement systems

4.8 Massachusetts Turnpike Authority

Facilities: Massachusetts Turnpike, Callahan, Sumner, and Williams Tunnels

Type of Facilities:	rural roadway, urban roadway, commuter tunnels
Length of Facilities:	135 miles
Average Daily Transactions:	437,000
Toll Configuration:	tickets rural, barrier urban, barrier tunnels
Toll Plazas:	22
ETC Equipped Plazas:	1
Toll Rates:	rural - to $5.10 autos tunnels - $1.00 autos, $2.00 commercial barriers - $.25 - $1.00 autos

The Massachusetts Turnpike Authority (MassPike) operates a rural ticket system, an urban barrier system, and three tunnels. Currently, only the Williams Tunnel, opened in December of 1995, utilizes ETC and is open only to commercial traffic. However, a contract for installing ETC on the remainder of the system is currently in negotiations.

The Williams tunnel is a likely location for a successful ETC program for several reasons. First of all, although it is restricted to commercial vehicles during weekdays until 2003-2005, the commercial traffic is heading for the airport on a frequent basis. Air freight carriers, limousine services, bus companies, and other fleets may use the tunnel several times a day. The convenience for such frequent users is obvious. Also, commercial vehicles are usually large fleets, who favor the benefits of single ETC accounts to track all toll transactions from a fleet of vehicles. Lastly, the tolls on the tunnel are too high for automatic coin collection lanes, which leaves only manual toll collection, or ETC toll collection. ETC collection is likely to be cheaper than all-manual collection, as note in Chapter 3.

Some key information for the ETC system follows:

Toll Lanes Total:	4
Mixed ETC/Manual Lanes:	2
Dedicated ETC Lanes:	2
ETC Market Penetration:	8.5%
Tags in Circulation:	2500
Toll Discount/Fee:	$5.00 for monthly statement
Tag Deposit:	$1000 surety bond or cash deposit
Payment:	Post pay
Installation:	User

The ETC penetration rate of 8.5% may seem low. However, this system (and the tunnel for which it collects tolls) had only been in operation five months at the time of the survey. Thus, the ETC market share is probably pretty good (other systems, such as E470 have a higher penetration rate, but also have been operating ETC for 5 years.) Dedicated ETC lanes are provided, despite a relatively low peak hour demand at the tunnel, which encourages ETC usage. Unfortunately, the bonding requirement is rather high at $1000, which may hurt ETC usage. Also note that this is the only post-pay system in the case studies. Although the authority does not seem to be having a problem with collecting on a post-pay basis, it is likely that non-commercial pre-paid accounts will be the norm on the rest of the MassPike system when ETC is made available everywhere.

The motivation for installing ETC was two fold: to make the turnpike more efficient and to enhance customer service. At this point, it is not possible to tell if the benefits will outweigh the costs of the system, since it is so new and only a small portion of the facilities are equipped.

For the current ETC system on the Williams Tunnel, ETC is very well liked, although MassPike has had problems getting taxi fleets to sign onto the program. This is due to the daily nature of transactions between taxi drivers and taxi companies, as taxi driving is a transient business. Also, due to unfamiliarity with ETC systems, taxi drivers feel they might have a hard time convincing their passengers that a toll is being paid (which must be added on to the rider's total fare) thus loosing revenue. On the other hand, non-ETC van and bus operators have been questioned by their patrons as to why they are not using ETC as ETC equipped vehicles pass by the toll queues in dedicated ETC lanes. Hence, the use of dedicated lanes helps to enhance public enthusiasm for the system, providing pre-publicity before the availability of ETC to all patrons on other parts of the system.

The remainder of the MassPike system will be converting to ETC in the years to come. It is likely, given the high number of repeat users on the other tolled tunnel (the Sumner) and the urban area barrier system, plus a large number of plazas per mile, ETC will be a success when installed on other parts of the system. The rural system is likely to be successful too, however perhaps to a lesser extent since repeat users are not as common on the rural section.

Obviously, since MassPike desires to use the same ETC tag on all of its facilities, including the rural ticket system, the tags are read/write technology. It is one of the few read/write systems used in the country.

MassPike spent a great deal of time in writing its procurement documents, which include the temporary ETC system for the Williams Tunnel. The document, *Toll Collection System Upgrade and Related Services: Request for Proposal*[38] gives the details of a complete overhaul of the toll collection system for MassPike. Instead of retro-fitting each plaza one by one, the proposal outlines changing the entire antiquated toll collection system, including manual and automatic coin lanes, to an integrated system including electronic toll collection.

Key lessons from Massachusetts Turnpike:

- Dedicated ETC lanes can be used to encourage ETC use
- Installation of tests systems can familiarize other patrons with ETC possibly helping future penetration rates

[38] Massachusetts Turnpike Authority, *Toll Collection System Upgrade and Related Services: Request for Proposal*, June 1995.

- Conversion of a large system to ETC at all locations is complex and requires coordination and good procurement documents
- It is difficult to get certain types of patrons to use ETC systems, such as taxicabs, due to unfamiliarity and the daily basis and per-trip account resolution that takes place.

4.9 General Ideas from Case Studies

There are several points and conclusions that can be drawn from looking at all of the case studies simultaneously. The areas covered are: technology, ownership arrangements, reliability, patron views, and success characteristics.

4.9.1 Technology

The type and technology of tags seems to currently be "read only" or Type I, using radio frequency. As one can see from the description of ETC technology given early in this paper, radio frequency is preferred for its high speed characteristics (allowing multiple error checking); lack of interference from lighting, cleanliness of tag, and speed of vehicle; and difficulty in reproduction. Although cross lane interference and interference from other sources is a concern with RF systems, it appears that these problems have been solved as no one reported major problems with tag reading reliability. General literature in the field has also confirmed that most radio frequency tag systems are very reliable. Also, as technology has advanced, the price of this type of tag has fallen.

The Massachusetts Turnpike is using an active tag system with a five year battery life. This does not mean that after five years the tag must be discarded, simply serviced and a new battery added. Other systems were not asked about whether their system was active or passive, or what the battery life might be.

Type II or "read/write" systems are seeing more use in the United States. As indicated in the case studies, the Illinois State Toll Highway Authority and the Massachusetts Turnpike

Authority are both using read/write technology (although neither system is currently using the write capability in a closed toll system). The Kansas Turnpike and the New York State Thruway, as noted earlier, both operate closed "read/write" ETC systems. Hence, as more and more closed systems move toward ETC, the standard is bound to become read/write technology based on the survey results given above and the increasing use of ETC on closed (or ticket) toll systems.

There is a noticeable lack of any use of smart card technology. (See Chapter 3 for an explanation of this technology.) It is likely that this technology is viewed as too advanced since the lower technologies seem to handle the desired function just fine. Perhaps, as integration of paying for different kinds of transportation services increases, this technology will be applied, but not in the near future.

4.9.2 Ownership and Operations Arrangements

Another key point to note is the fact that all the case studies indicated that they own the toll collection equipment (including ETC equipment) and collect there own tolls, with the exception of the E470 Public Highway Authority, which owns the equipment but collects tolls through an operations contractor. The option of leasing equipment has not been used as a permanent arrangement on any of the case studies. (From other publications, it is noted that during pilot test phases in the past, equipment is frequently leased and returned at the end of the pilot.)

It is likely that this trend of ownership will continue into the future for pre-existing toll facilities. However, new facilities built under public/private contracts (such as the SR91 project in California) will probably use leasing arrangements since the entire roadway is operated by the private entity which may be more likely to lease equipment than to buy it.

It appears that there is much to be gained from leasing equipment, especially given the high capital cost of ETC systems, but traditional toll authorities have either decided that the costs are lower for purchasing, or are hesitant to enter into such arrangements. New alternative leasing arrangements have been discussed previously in Section 3.4.3.

All case studies indicated that they run their own accounting and tag offices. This seems likely given the ownership arrangements discussed by all case studies. But once again, it may be less costly to concession out tag store operations, especially if many tag stores exist, such as on a large system. Cost savings come from the areas of overhead and public employee benefit rates which are high for most authorities but can be lower for private concessionaires.

4.9.3 Reliability

All five case studies indicated very few problems with tag reliability. Perhaps this is because procurement documents are now written with very high reliability rates. Also, since the technology for ETC has been advancing over the last decade or so, reliability has increased. At this point, reliability is no longer an issue, once a system is calibrated and antennas aligned properly. However, it is possible that a sub-standard equipment manufacturer may install equipment which is unreliable, therefore it is still necessary to be exacting in procurement documents about reliability specifications and repair times.

The high level of reliability will also help toll authorities sell their system to patrons. Patrons most likely worry that they will be charged incorrectly or their accounts may be altered accidentally. By citing high levels of reliability on other systems and writing procurement specifications with high reliability requirements (like recommended standards from ITS America) these fears can be alleviated. As ETC becomes more common place and its familiarity and accuracy are better known, patron hesitancy over reliability will be less of a problem.

4.9.4 Patron Views - Opinions of Programs and Privacy

All of the case studies indicated, despite their statements about whether or not the benefits have exceeded the costs, patrons generally liked their ETC program. Keeping this in mind, it is likely that ETC will see more and more favorable applications in the future. As mentioned in Chapter 3, ETC is also being promoted as a way to convince the public that tolls are not as bad of a thing as they might think. The case studies show that the trend is toward this end.

In addition, few patrons questioned the privacy of ETC systems. This is likely due to those individuals who are concerned about privacy not using the ETC tags, but paying tolls by more traditional methods instead. (All of the case study systems indicated that they do not have anonymous ETC accounts available for such patrons.)

Another indicator of the public opinion of ETC systems is that Illinois and Massachusetts both responded that they are expanding their systems, covering more plazas, more lanes, and more patrons. If the opinions of the system were negative or privacy concerns were large, these plans would probably not be in place.

4.9.5 Success Characteristics

Measuring the success of an ETC installation is very difficult. Frequently information on costs and benefits is defined differently for each application, making comparisons complicated. However, some of the prime characteristics include: depth of ETC penetration, changes in cost of toll collection, patron satisfaction, changes in revenue, and changes in queuing and congestion around plazas. Unfortunately, only depth of ETC penetration is commonly available as a success characteristic, as noted earlier.

Depth of ETC penetration is a very important characteristic for the success of ETC programs. As can be seen in the case studies, the following ETC penetration rates exist:

Illinois:	1%
Dallas:	40%
E470 Denver:	33%
Lincoln Tunnel New York:	30% of eligible
Williams Tunnel Boston:	9% of eligible

Clearly those systems which offer ETC at the majority of their plazas have a higher usage rate. As mentioned, Illinois has only a few plazas equipped with ETC and a consequent low participation. In addition, their tag deposit is fairly high for autos, and credit cards are not used as a payment option. Dallas and E470, on the other hand, both have a high percentage of ETC plazas and lanes, with some variation in tag deposit. The New York and Boston studies are both special cases. The New York facility does do fairly well with 30% of eligible transaction done by ETC and the Williams Tunnel is showing a growing ETC penetration rate since its recent opening.

All of the case studies do not have extra charges or discounts on tolls (except for deposits and account balances) which might affect ETC penetration rates. However, if one examines public data from other systems, various discount levels have produced better ETC penetration rates in some instances, as shown in table 4.2:

Table 4.2
ETC Participation Rates and Discounts Offered

Tappan Zee Bridge New York	75% ETC Use with 50% toll discount
Lake Pontchartrain Cswy (New Orleans)	80% ETC Use with 50% toll discount
Crescent City Connection (New Orleans)	30% ETC Use with 50% toll discount
Oklahoma Turnpike	45% ETC Use with 10% toll discount

Sources: IBTTA, *ETTM System Survey*, March 1995; Marcella and Boss, "Evaluating Market Demand", *1995 IBTTA International ETTM Symposium*, pg. 64; NCHRP Synthesis 194, pg. 12.

Those systems with extraordinarily high ETC use offer deep discounts on tolls. (Although, in the case of the Crescent City Connection, the discount does not seem to have helped much.)

Unfortunately, discount programs are unavailable to many toll authorities since their bonding requirements forbid it. Nevertheless, as has been noted in the Dallas North Tollway case study, high ETC usage rates (40%) can be achieved without discounts, due to a high profile tag store, all plazas being equipped with ETC, a low tag deposit, etc.

Achieving the highest possible ETC market penetration may not be the way to go for toll authorities, as mentioned earlier. The goals of the agency must be taken into account. A justification for achieving high usage rates may be to decrease toll collection costs. For instance, the Tappan Zee Bridge has a toll which is high enough not to use ACM machines, so all tolls are collected manually, which is expensive. By encouraging higher ETC use, they may be achieving lower toll collection costs. Also, during rush hour, the authority may be trying to alleviate congestion and increase throughput without expanding the physical toll plaza by encouraging high ETC usage. Other systems, such as the Illinois study, may have a goal of increasing patron convenience, which would not lead them to encourage ETC usage at all costs, such as deeply discounting tolls.

The other success characteristics are generally not available for a wide range of systems. Owing to the newness of many of the systems, and lack of standardized reporting, many of these characteristics will not be available for some time. Efforts clearly need to be made to obtain better success characteristics and evaluations of ETC systems than is currently being performed.

4.9.6 Case Study Conclusions

Putting all this information together, it is possible to come up with some conclusions from the case studies, which are consistent with the design recommendations outlined earlier. First, ETC programs are generally successful and well liked by patrons using them. Second, it is important to have a good publicity campaign, ease of purchase and installation, and have ETC available at many plazas upon start up, in order to achieve high (20% - 40%) penetration rates. Third, ETC programs take much longer to fully install on larger facilities than on smaller facilities. Lastly, ETC use is more likely during peak hours at highest congestion plazas probably due to the number of commuters and likelihood that a patron must pass through this most congested plaza.

Another important point to make is the use of ETC by fleet vehicles, such as in the case of the Williams Tunnel in Boston and the Lincoln Tunnel in New York. Both of these successful programs (as well as the Oklahoma program not used as a case study) are specifically designed to cater to large clients of the toll authority, such as bus and trucking companies. These client have many toll transactions recorded per year and find the convenience and accounting involved with ETC much better than older payment receipt systems.

Finally, the evaluation of ETC systems is very difficult at this time. Typical reporting and survey efforts have not evaluated systems. More work needs to be done comparing several systems and getting in-depth information on authority motivations, cost and benefits, future plans, and predicted growth.

Some conclusions from the case studies are also very important for the Puerto Rico analysis, given in Chapter 7. First, the general statements that benefits exceed costs in most ETC situations and that patrons like ETC programs reflects favorably on the installation of ETC in Puerto Rico. Second, the use of the exclusive bus lane at the Lincoln Tunnel may provide a model for a similar bus/HOV lane in Puerto Rico at major toll plazas. The time savings achieved from such an exclusive lane may encourage people to use these less polluting, less congestion causing modes of travel. Third, the problem of enforcement on both the Illinois tollways and the Lincoln Tunnel may indicate problems of enforcement for Puerto Rico, especially since toll evasion is common on toll facilities in Puerto Rico. (See Chapter 7 for more details.)

Chapter 5

Queuing and Capacity Model

The purpose of this chapter is to outline simple techniques which can be used to analyze the capacity at a given toll plaza, and look at the queuing characteristics of a plaza over the course of a day. Results from the techniques include available capacity, maximum waiting time, average waiting time for those who wait, and maximum queue.

From the literature review for this research, it was found that the most information available for design and analysis of electronic toll collection (ETC) systems is in the area of capacity and queuing. Many private consulting firms, universities, and organizations have published and developed various forms of capacity analysis. Some are fairly simple, straight forward queuing analysis systems using average capacity rates for various types of toll lanes. Others are very complex micro-simulators which require an abundance of computing power and programming knowledge. All models, however, utilize a pre-assumed lane configuration and depth of ETC market penetration to examine how the queuing at a toll plaza occurs through the time variant peaks of an average day. The point is to evaluate if ETC increases capacity and reduces queues during the peak period, has no effect, or actually lowers capacity and worsen queues. The models also help designers to choose lane configurations which are appropriate to approaching traffic mix.

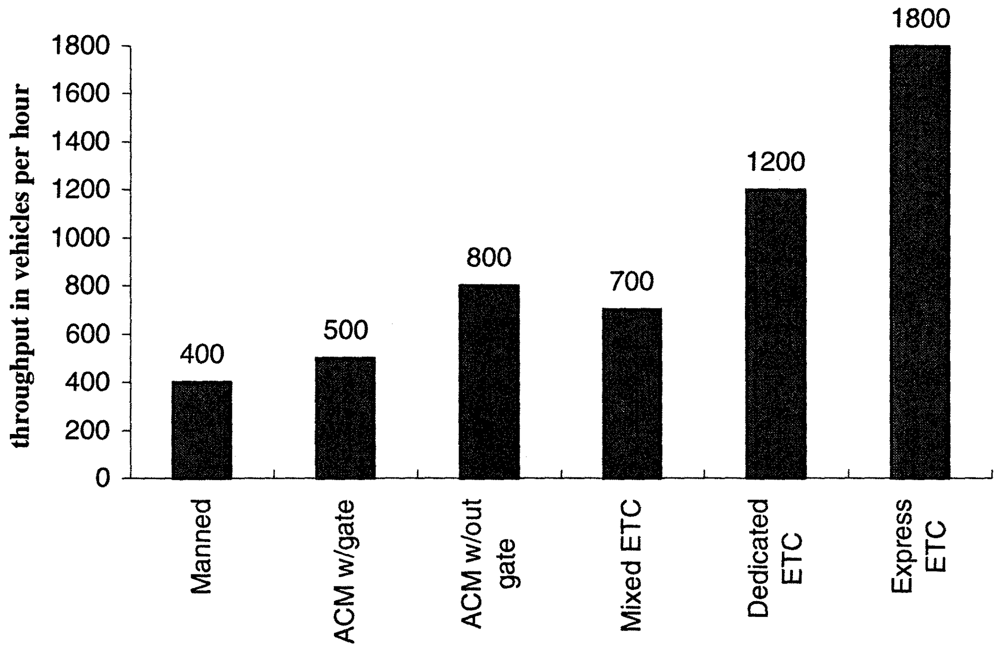
Fortunately, a fairly simple and straightforward capacity and queuing analysis can be done with data available to most toll authority planners and a spread sheet program on a microcomputer. This is the type of model developed here. It is designed as a rough estimation procedure that takes very little time to complete. The output of the model includes capacity based on any type of proposed lane configuration, possible reduction in queue lengths and waiting times, and a good idea of which lane configuration will work best given a particular level of demand and ETC participation rate.

5.1 Capacity Analysis

In order to construct a model for a toll plaza, it is first necessary to determine the amount of throughput each lane will achieve when at peak capacity. This can be determined through regular toll audits by examining the maximum number of patrons handled by each type of lane on a system, during the peak rush hour, when queues exist for the entire hour. Since most toll facilities experience peak loading at the regular rush hours of the day, it is recommended that data for a regular weekday under normal conditions be used to determine this throughput. "Regular" implies conditions where lane capacities are not affected by bad weather, a plaza equipment malfunction, an accident near the toll plaza, holiday traffic, construction near the toll plaza, etc. If there are not queues during the entirety of the peak hour, the number processed during the peak fifteen minutes (or some other fraction of an hour) when a queue exists can be used if it is normalized to the vehicles per hour flow. (i.e. for a fifteen minute peak, the number processed would be multiplied by four to get the possible maximum processing rate per hour.) The maximum processing rate figure for each type of lane (i.e. manual collection, automatic coin collection, token collection, etc.) can be improved by using data averaged over several "regular" days and similar lanes.

Of course, lane types which do not exist can not be analyzed in this manner. Instead, measurements from other facilities that utilize special types of lanes, such as express ETC lanes, must be used in lane configuration capacity analysis. Figure 5.1 shows a summary of currently accepted throughput rates for various types of lanes. If data is unavailable on existing lanes, those given here can be used. However, it is important to note that there are sometimes significant differences in the throughput of traditional lanes across facilities, and that getting data from the facility under study is preferred.

Figure 5.1
Capacity of Toll Lane Types



Sources: -*Electronic toll and Traffic Management (ETTM) Systems,* NCHRP Synthesis 194, Transportation Research Board, 1993.
-*Evaluating the Improvements in Traffic Operations at a Real-Life Toll Plaza with Electronic Toll Collection*, H.M. Al-Deek et al, University of Central Florida, December, 1995.
-*ETTM Is Great But-*, Greenbaum, D.W., IBTTA 61st Annual Meeting, October, 1993.

Although all types of lanes shown in Figure 5.1 are in use across the United States, the automatic coin machine lane (ACM) w/out gate option is rarely chosen due to the loss of revenue and difficulty of enforcement associated with such lanes. Also, some agencies utilize special means of speeding up toll collection on traditional lanes. "Lane-walkers" are personnel who stand next to ACM machines, collect the exact change from the motorist, throw it in the ACM basket, and pre-empt the gate arm, allowing the collection rate to increase. Another capacity technique is the use of "double lanes" where two toll booths are set up on the lane, serving customers in tandem, and increasing lane capacity.

The next step in this analysis is to determine the current capacity of a toll plaza. For instance, an 18 lane toll plaza may consist of 14 lanes in the peak dominant direction, 6 of which are manual, and 8 of which are automatic coin collection machines (ACM) with gate arms. For the remainder of this chapter, only the 14 lanes open in the dominant direction will be considered. (The lanes in the non-dominant direction are assumed to be un-useable for the dominant direction analysis. See Chapter 7 for an analysis including the non-dominant lanes.)

The theoretical capacity of this plaza is 6400 vph as shown in Table 5.1.

Table 5.1

Capacity of 14 Lane Toll Plaza (14 lanes in peak direction)

number/type of lane	capacity per lane (vph)	total capacity (vph)
6 manual lanes	400	2400
8 ACM lanes	500	4000
Total Capacity		6400

If the mix of traffic approaching the plaza is compatible with the lane arrangement, the full 6400 vph capacity is available. For instance, if 2400 vph or less patrons who need to pay manually and 4000 vph or less patrons who have exact change are approaching the plaza, then the capacity of 6400 vph handles the total demand of 6400 vph.

However, if many of the patrons approaching the plaza want to pay manually and get change, this capacity would seriously decrease. For instance, if only 3200 vph during the peak will use the ACM lanes, and 3200 want to use the manual lanes, the available capacity is 5600 vph, even though the total demand is the same at 6400 vph. (See Table 5.2.) Here, the capacity is the minimum of the lane capacity and the demand for a given lane type. The manual lanes are short of capacity by 800 vph. Over time, a queue will build up in the manual lanes whereas the ACM lanes will generally not have a queue. Thus the total available capacity of the plaza is reduced by 800 vph to 5600 vph. This concept of plaza capacity being decreased by the demand for specific types of toll lanes is very important throughout the analysis here and in Chapters 6 and 7

If the demand for ACM lanes is higher than the ACM capacity, for instance 5000 vph, and manual lane demand is 1400 vph, the available capacity is not decreased in the same way as the previous situation since ACM patrons always have the option of using the manual lane. In addition, since ACM customers frequently have exact change, manual lanes processing these customers may exceed their estimated capacities given here, since there is no time spent in making change for the patron. This would again contribute to higher plaza capacity despite the mismatch between market share for different types of lanes and actual lane configuration.

Table 5.2

Capacity of 14 Lane Toll Plaza (3200 vph ACM, 3200 vph manual)

number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
6 manual lanes	2400	3200	2400
8 ACM lanes	4000	3200	3200
Total Available Capacity	6400	6400	5600

This concept becomes very important when ETC is installed at a plaza. If a large amount of ETC capacity is installed at a plaza, with the intention of increasing overall capacity, the ETC market may not utilize all the available ETC capacity. Thus, the available capacity of the whole plaza is reduced. In the extreme case where a very large amount of ETC capacity is installed, while removing manual and ACM capacity, the available capacity of the plaza may decrease below the pre-ETC capacity.

The next question to ask is, "How many ETC lanes should be installed at this location?" in order to avoid installing too much ETC capacity. To answer this question, the peak period demand should be examined. For this example, the peak demand is 6400 vph. It is also necessary to estimate ETC market penetration at this point. For an ETC program which is just starting up, a possible ETC market penetration is 10%, based on the case studies and design criteria presented earlier. This gives a total demand of 640 vph for an ETC lane (6400 vph demand * 10% ETC penetration.) From Figure 5.1, it can be seen that converting one ACM lane to a mixed ETC / ACM lane would be advisable to take up this demand. Now, the theoretical capacity of the plaza has increased, as seen in Table 5.3, to 6600 vph.

Table 5.3 **Capacity of 14 Lane Toll Plaza - ETC Equipped**		
number/type of lane	capacity per lane (vph)	total capacity (vph)
6 manual lanes	400	2400
7 ACM lanes	500	3500
1 ETC/ACM mixed lane	700	700
Total Capacity		6600

Suppose all the ETC users are previous ACM patrons. Table 5.4 shows the capacity break down for the 2400 vph manual / 4000 vph ACM split for the traditional collection methods, with 640 of the ACM customers converted to ETC.

Table 5.4 **Capacity of 14 Lane Toll Plaza (3360 vph ACM, 2400 vph manual, 640 ETC)**			
number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
6 manual lanes	2400	2400	2400
7 ACM lanes	3500	3360	3360
1 ETC/ACM lane	700	640	640
Totals	6600	6400	6400

The available capacity of this configuration is 6400 vph, which satisfied the demand, with some extra room to spare in the ACM and ETC lanes. (The theoretical capacity, if the proper traffic mix existed, is 6600 vph, an increase of 200 vph over Table 5.1.)

However, the typical problem with installation of ETC lanes is not the former traffic mix, but rather the depth of ETC penetration. For instance, if a manual lane is changed to a dedicated ETC lane (and the former mixed ETC lane is kept), then the results in Table 5.5 would be found.

Table 5.5 Capacity of 14 Lane Toll Plaza (3360 vph ACM, 2400 vph manual, 640 ETC)			
number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
5 manual lanes	2000	2400	2000
7 ACM lanes	3500	3360	3360
1 ETC/ACM lane	700	0	0
1 ETC dedicated lane	1200	640	640
Totals	7400	6400	6000

Here, the theoretical capacity has increased from the original, non-ETC configuration by 1000 vph, yet the available capacity has decreased by 400 vph. This is due to having too much ETC capacity for the traffic mix approaching the plaza. Also note, although the demand for the mixed lane appears to be zero, it is likely that some of the ACM customers would use this lane, and perhaps some of the ETC customers, but it is mostly excess ETC/ACM capacity. It would be better used as a manual lane to take up the extra demand in the manual market. Hence, the chosen lane mix must be compatible with the market mix of patrons to achieve maximum capacity.

For an application of these concepts to actual plazas, see Chapters 6 and 7.

5.2 Queuing Analysis

Once the capacity of the current and future configurations of the toll plaza is determined, queuing effects can be examined. Table 5.6 shows an assumed demand, broken down by hour, for the section of roadway the toll plaza is on for the morning peak hour, in the peak direction. (In most situations, the morning peak hour is the heaviest repetitive demand for a toll plaza. It is this peak demand for which the plaza must be designed.)

Table 5.6 **14 Lane Toll Plaza, Morning Rush Hour, Peak Direction Demand**			
Hour	Demand	Hour	Demand
5-6 AM	2000	8-9 AM	7400
6-7 AM	6000	9-10 AM	4000
7-8 AM	9400	10-11 AM	2000

In order to determine the queue build up and dissipation, first the capacity of the plaza must be determined (see Section 5.1). For this example, the original toll lane configuration of 6 manual and 8 ACM lanes from Table 5.2 is used. The traffic mix approaching the plaza is assumed to match the configuration, and available capacity is the total capacity, 6400 vph (i.e. the proportion of demand for manual lanes as a part of the total demand matches the proportion of manual lanes available as a proportion of the total.) Table 5.7 shows the total queue build up and dissipation during the morning rush hour.

Table 5.7

14 Lane Toll Plaza Queuing (6400 vph max. cap., manual and ACM only)

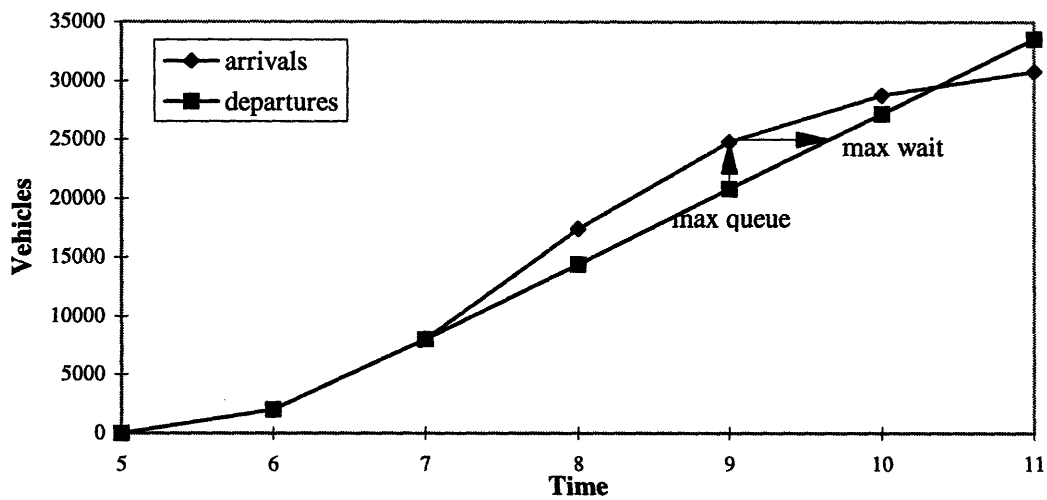
Hour:	Demand: (vph)	Capacity Shortage: (CS) CS=Demand-6400	In Queue: (IQ) IQ = previous hour IQ + current CS If IQ < 0, enter 0
5-6 AM	2000	-4400	0 + (-4400) = 0
6-7 AM	6000	-400	0 + (-400) = 0
7-8 AM	9400	3000	0 + 3000 = 3000
8-9 AM	7400	1000	3000 + 1000 = 4000
9-10 AM	4000	-2400	4000 + (-2400) = 1600
10-11 AM	2000	-4400	1600 + (-4400) = 0

A queue exists of 3000 cars at the end of the 7-8 AM hour, 4000 cars at the end of the 8-9 AM hour, and 1600 cars at the end of the 9-10 AM hour.

(Note that these numbers, are of course, quite large. It is unlikely that any toll facility would be operating under such crowded conditions. However, large numbers are used to illustrate the computational technique used and the graph below.)

Another way of looking at this queue situation is to graph the cumulative departures (6400 vph) with the cumulative arrivals (varying per hour) as shown in Figure 5.2.

Figure 5.2
14 Lane Toll Plaza Queuing, Morning Peak



Here it can be seen that the arrival rate exceeds the departure rate beginning at 7 AM, when the queue starts to form, and disappears around 10:20 AM. The departures line is equal to the arrivals line as long as the capacity of the plaza exceeds the arrival rate, and thus the departures line follows the arrivals line for this period (5:00 to 7:00 AM). During this time there is no queue for the toll lanes. When the arrival rate exceeds the departure rate, a queue begins to form and the departure rate is equal to the capacity of the plaza. The departures line increases at the maximum capacity rate, while the arrivals line increases according to the arrivals given in Table 5.7. This period lasts from 7:00 AM to about 10:20 AM. When the departures line meets the arrivals line, the queue dissipates (at 10:20 AM). For the remainder of the time period, no queue exists as capacity exceeds arrivals.

The area between the two lines is the total waiting time experienced during the morning peak. The longest queue occurs at the place where the vertical space between the lines is at a maximum (at 9:00). The longest wait time is the maximum horizontal distance between the two rates, extending from approximately the 9 AM mark on the arrivals line to the 9:40 AM mark on the departures line - for a maximum delay time of 40 minutes. (This is, again, exceptionally large. The data used here has been chosen such that the graphs of the queuing process are easier to read.) The average wait for each patron over the course of the entire day can be calculated by determining the total area between the two lines and dividing it by the total number of patrons processed over the period. Also, the average wait for those who had to wait in queue can be calculated, as described later.

There are some assumptions being made with this type of queuing analysis. First of all, deterministic arrival rates are assumed throughout each hour. It is, of course, unlikely that arrival rate will be deterministic or that the rate will change at exactly the beginning of the hour. Random arrival queuing, wherein the average arrival rate changes constantly throughout the day, would be a closer statistical process to model this queue. In addition, service times will also vary randomly based on the amount of time each patron takes to complete a transaction. The effect of both of these statistical processes would be to increase the average waiting time as the variability of the arrival and departure rates increase. However, the purpose of this model is to determine a first rough estimate of the delay under differing capacities and demand scenarios. It is also rarely possible to gain the precise data needed to make random queuing functional since a rather detailed study of the roadway approaching the toll plaza and the toll transaction process would be needed. Instead, the model described here uses the demand on the roadway per hour of the day which is frequently available from the metropolitan planning organization (MPO) for the area where the facility exists. MPOs can also typically provide future year forecasts for hourly demands, which, when used in this model, can be helpful in determining the number and type of lanes needed in the future at a toll plaza (whether ETC is installed or not.)

Obviously, drawing a graph such as in Figure 5.2 is one way to measure the operating characteristics for the configuration and demand at the toll plaza. However, a faster method can be created using a simple spreadsheet program. The details of this development are left to Appendix B. Table 5.8 shows the results from one such model.

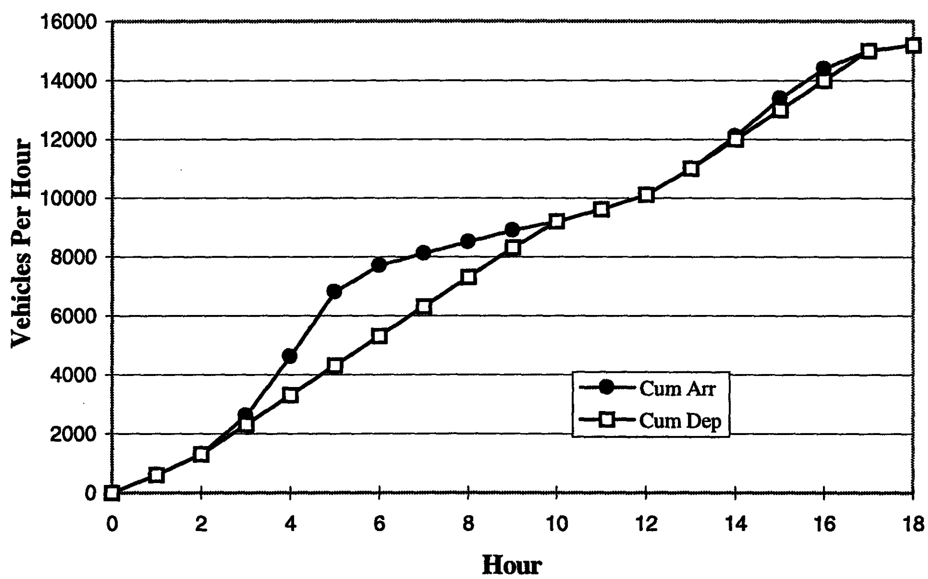
Table 5.8

14 Lane Plaza Queuing Example Spreadsheet Results

A Hour	B Arrivals (vph)	C Cum Arr (vehicles)	D Departures (vph)	E Capacity Shortage (vph)	F Q Length (vehicles)	G Cum Dep (vehicles)	H Tot Delay (vehicle hours)
0		0	1000		0	0	0
1	600	600	1000	-400	0	600	0
2	700	1300	1000	-300	0	1300	0
3	1300	2600	1000	300	300	2300	150
4	2000	4600	1000	1000	1300	3300	950
5	2200	6800	1000	1200	2500	4300	2850
6	900	7700	1000	-100	2400	5300	5300
7	400	8100	1000	-600	1800	6300	7400
8	400	8500	1000	-600	1200	7300	8900
9	400	8900	1000	-600	600	8300	9800
10	300	9200	1000	-700	0	9200	10057
11	400	9600	1000	-600	0	9600	10057
12	500	10100	1000	-500	0	10100	10057
13	900	11000	1000	-100	0	11000	10057
14	1100	12100	1000	100	100	12000	10107
15	1300	13400	1000	300	400	13000	10357
16	1000	14400	1000	0	400	14000	10757
17	600	15000	1000	-400	0	15000	10957
18	200	15200	1000	-800	0	15200	10957

Figure 5.3 shows a graph of the cumulative arrivals and departures. Note that there are two queues. The first starts forming at hour 2:00, and the second at hour 13:00. The maximum queue can be determined directly from the table as 2500 vehicles. The total wait time for the first queue is 10,057 vehicle hours (the cumulative wait time when the first queue ends.) For the second queue, it is 10,957 - 10,057 or 900 vehicle hours. To determine the average wait time, it is only necessary to divide the wait time by the number of vehicles serviced. For example, for the entire time period, 10,057 vehicles hours of wait occurs while 15,200 vehicles are processed (cumulative arrivals).

Figure 5.3
14 Lane Toll Plaza Queuing Hourly Graph



Provided no queue exists at the end of the time period under study:

Average Wait Time = 10,957 veh.*hrs. / 15,200 veh. = .72 hours

Another valuable calculation is the average waiting time for those patrons who have to wait in queue. By examining the arrival curve, one can see that those who have to wait are all those who arrive while there is a queue. The total wait time for one of the queues divided by the total number of arrivals while this queue exists would be the average wait time for that queue. From the beginning of hour three until the end of hour nine, (and beyond) there is a queue. The total number of arrivals in this time period is:

8900 (Cum Arr 9:00) - 2600 (Cum Arr 3:00) = 6300 vehicles

Also, there are some number of patrons who must wait during the tenth hour while the remainder of the queue, which is 600 vehicles, dissipates. The difference between the departure rate and arrival rate during the tenth hour is the rate at which the remainder of the queue dissipates. For this example:

1000 vph (Departures) - 300 vph (Arrivals) = 700 vph Queue Dissipation

Next, find the fraction of the hour it takes the queue to dissipate, which is the ratio of the queue remaining at the end of the previous hour, divided by the dissipation rate:

600 veh / 700 vph = .8571 hrs

So, the arrivals during this fraction of the hour will have to wait in line, which is equal to the fraction of the hour multiplied by the arrival rate:

.8571 hrs * 300 vph = 257 vehicles

Adding this amount to the total number of vehicles waiting from hour three to hour nine:

6300 veh + 257 veh = 6557 vehicles waiting in first queue

Also, the total delay encountered in the first queue is given at hour ten as 10,057 vehicle hours. So, the average wait time, for those who have to wait in the first queue, is the wait time divided by the number of vehicles waiting:

10,057 veh*hrs / 6557 veh = 1.53 hrs

Thus patrons which have to wait in the queue are waiting for 1.5 hours on average. (Clearly, this is a very long wait time, but once again one must remember the data was chosen to clarify the queuing calculations. More practical data and calculations are given in Chapters 6 and 7.)

Finally, the maximum delay can be approximated. This is somewhat more difficult to calculate since the maximum delay is the longest horizontal area between the cumulative arrival and departure lines. To calculate maximum delay, select the row with the highest arrival rate (column B). Then, find the cumulative arrivals and time at this point.

For the example above, these are: Max Arr = 2200 vph, Cum Arr = 6800 vph, Hour = 5:00

Then find the time period during which this cumulative arrival figure is equaled by the cumulative departure figure. It will most likely occur between two time points:

For this example: Cum Dep = 6300 Time = 7:00
Cum Dep = 7300 Time = 8:00

Next, compute the fraction of the hour where the cumulative arrivals meets cumulative departures.

For this example: (6800-6300)/(7300-6300) = 500/1000 = .5

Hence, the maximum wait time line meets the cumulative departures at:

7:00 + .5 hours = 7:30

Then, the longest waiting time is the difference between this figure and the hour where the maximum arrivals occurred. For this example:

7:30 - 5:00 = 2.5 hours maximum wait time

(A maximum wait time of 2.5 hours is, again, clearly unreasonable. Remember the numbers used in this graph were designed to exaggerate the areas of delay in order to illustrate the process. It is unlikely any toll authority would be operating under such poor conditions.)

Table 5.9 gives a summary of the statistics calculated for this model.

Table 5.9

Statistics for 14 Lane Plaza Queuing Example

Maximum Queue:	2500 vehicles	Total Wait Time:	10,957 vehicle hours
Average Wait Time:	.72 hours	Maximum Wait Time:	2.5 hours
Ave. Wait, 1st Queue:	1.5 hours	Ave. Wait, 2nd Queue:	.23 hours

The average wait time and average wait times for those who wait in queue are very important indicators of the level of service experienced by the patron. The length of time spent in line is probably the number one measure patrons use to determine their satisfaction with the tolling process, (with amount of toll paid being second.) Hence, the average wait times can be interpreted as the level of service offered to customers.

5.3 Use of Models

The capacity determination and queuing models presented here are meant to provide a rough approximation of the capacity and waiting times associated with a particular plaza in a particular direction. They provide a quick means to test various lane configurations based on either current or future projected traffic, and current or future technology (such as the capacity expansion provided by ETC.) The calculations for a simple spreadsheet are presented which can help in this analysis. A word of caution is advisable, however. Since many approximations and assumptions were made in the development of these models, they provide estimates that are generally acceptable, but not the basis for which major capital expenditures can be made. Software for random queuing models, which should be more accurate than those described here, has recently become available on the commercial market. With a bit more analysis and mathematical understanding of toll plaza models, these packages can provide better design information than the method presented here.[39]

This chapter has covered a hypothetical plaza with some clearly unreasonable data. An illustration of practical use of these models on real data and plazas is given in Chapters 6 and 7.

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[39] Pati, B. R., "Designing Efficient Toll Plazas Using IQPAC", *PC-Trans*, Winter Quarter 1996, pp. 14-18.

Chapter 6

Capacity and Queuing on the Massachusetts Turnpike

In this chapter, the model developed in Chapter 5 is applied to plaza 19 of the Massachusetts Turnpike (MassPike). Capacity analysis under current and future conditions, both with and without an ETC system will be presented, and queuing analysis for current and future conditions, with ETC installation, will also be presented.

The capacity of the plaza will be determined using actual lane configurations and processing data. Current demand data from Boston's Metropolitan Planning Organization (MPO) is combined with design criteria in Chapter 3 and theoretical lane capacity given in Chapter 5 to determine a possible optimal lane configuration if the plaza is equipped with ETC for current year demand levels. The ETC configuration will be shown to handle all current traffic (which the current non-ETC configuration does not do) while allowing one lane to be closed.

Capacity analysis under future year demand will include non-ETC and ETC configurations. The demand for a 10 year forecast is estimated by assuming a reasonable traffic growth rate for the plaza. Then, it will be shown that the plaza will need expansion without ETC in 10 years. However, with the installation and growth of an ETC system in 10 years, it will be shown that plaza expansion is not needed, and one lane may actually be closed, while still meeting future demand.

Next, a queuing analysis will be performed for the current year non-ETC configuration, showing the use of the queuing model for a real situation. This will then be compared with a queuing analysis of the current year demand with the ETC in place.

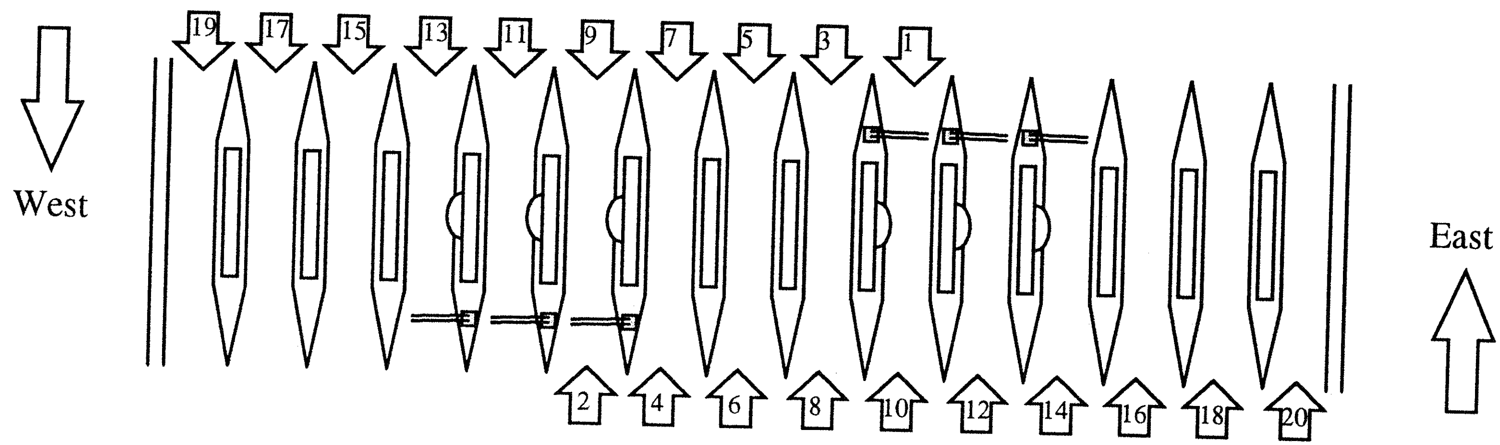
Under the 10 year future forecast with the current lane configuration (i.e. no expansion of the plaza or ETC system), a queuing analysis is presented showing the increase in waiting times and queue lengths. This is the perhaps the most useful function of the queuing model. The probable deterioration of the level of service (i.e. average and maximum waiting times) is very visible in this type of analysis. Then a comparison with the suggested expanded plaza, or more favorably, the plaza with a strong ETC program is made.

Plaza 19 of the Massachusetts Turnpike, located in an urban area, consists of 15 physical lanes, of which 5 are reversible. Figure 6.1 gives a graphic layout of the plaza and the equipment available. (Reversible lanes are given two numbers in the diagram, one for each direction. A type of lane will be associated with each direction. For instance, lane 9 is an ACM lane when operated for west bound traffic. However, it is a manual lane when reversed for eastbound traffic and is referred to as lane 2. When operated eastbound, the lane 9 gate arm is left in the open position, of course, in order to allow patrons to enter the toll lane.)

Peak hour transactions in the dominant direction during the morning peak reach about 4900 vehicles as shown in Figure 6.2. Also, from Figure 6.2, it can be seen that the morning rush is eastbound and the evening rush is westbound. Note that this figure shows the total number of transactions, not demand. Since the plaza experiences some queues during the peak hour, the actual demand is higher than the number of reported transactions. Also, according to Figure 6.2, the peak demand for the day occurs during the morning peak, with the demand in the evening peak being somewhat lower. Therefore, the remainder of this analysis will be for the morning peak.

(One special note should be made here: although plaza 19 is a mainline barrier plaza where all traffic must stop, it is located at a major interchange with other arterials in the area. There are two ramp plazas that feed the section of roadway around plaza 19. These plazas toll those who are leaving or entering the main roadway, since they will not pass through plaza 19, where those passing through the interchange on the main roadway are tolled. Although the study performed here shows capacity and queuing theories for plaza 19 only, the whole interchange should be analyzed as a unit. However, for simplification, only plaza 19 will be analyzed here.

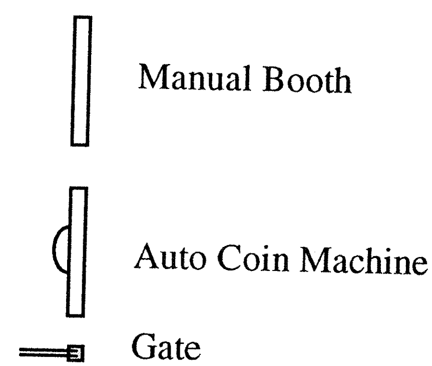
Figure 6.1: Current Plaza 19 Lane Configuration, Massachusetts Turnpike



Key:

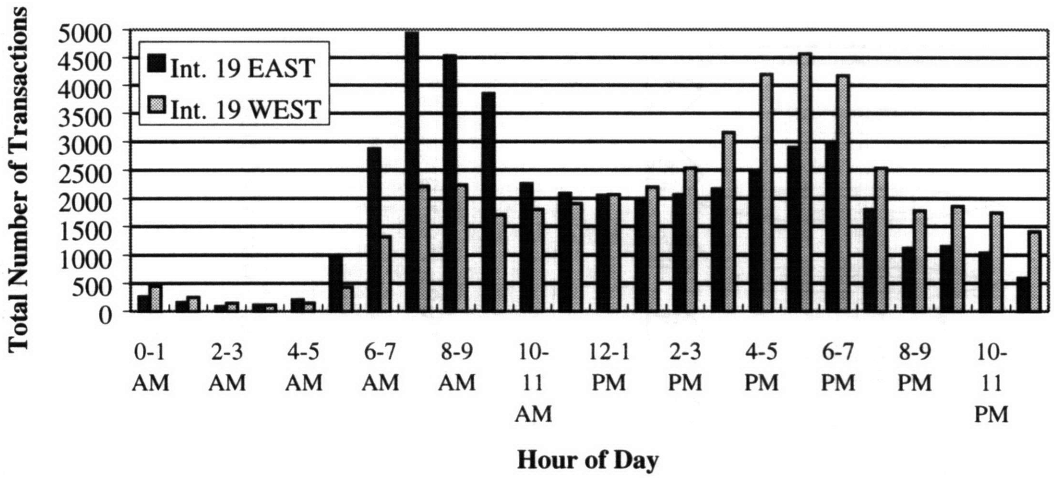
Lanes	15-20	Manual
Lanes	9-14	Automatic Coin
Lanes	1-8	Manual

Note that although lanes 1 and 2 appear to have ACM machines, the machines are located on the wrong side of the vehicle from the driver, and are thus manual only lanes.



Source: Massachusetts Turnpike Authority, *Toll Collection System Upgrade and Related Services*, June 1995, amended

Figure 6.2
Toll Transactions at MassPike Plaza 19 for Average Weekday



Source: Massachusetts Turnpike Toll Audit Department, 4/4/96 Hourly Counts

6.1 Capacity Analysis Under Current Demand

Using the method described in Chapter 5, a capacity analysis of the current toll plaza configuration is given in Table 6.1, for the dominant direction.

Table 6.1

Capacity of MassPike Plaza 19, East or West, -all 10 lanes open in dominant direction

number/type of lane	capacity per lane (vph)	total capacity (vph)
7 manual lanes	400	2800
3 ACM lanes	500	1500
Total Capacity		4300

As noted in the plaza diagram, 10 lanes in the dominant direction can be opened at any one time. The theoretical capacity of the plaza, 4300 vph, is lower than the highest reported transaction rate of 4930 vph, from the Massachusetts Turnpike Audit Department.[40] This is most likely due to faster processing on the manual lanes since the toll at this plaza is relatively flat ($.50 for autos) and many peak hour commuters would have correct change. Thus a more probable manual lane capacity might be 465 vph. Also, faster processing on ACM lanes is possible with newer gate technology. A more probable capacity is 550 vph for ACM lanes. Now the "theoretical capacity" is 4905 vph, as it appears in Table 6.2. (Given the other approximations made for this analysis, a theoretical capacity of 4905 vph is close enough to the 4930 vph maximum processing rate without causing significant errors further on in the calculations. As mentioned in Chapter 5, a better maximum capacity figure for each type of lane can be calculated by using actual hourly lane counts for individual lanes, if desired. This type of data was not available for this particular analysis.)

Table 6.2

Capacity of MassPike Plaza 19, East or West, -10 lanes open in dominant direction, corrected throughputs

number/type of lane	capacity per lane (vph)	total capacity (vph)
7 manual lanes	465	3255
3 ACM lanes	550	1650
Total Capacity		4905

The current capacity does not fulfill the demand at the plaza for the morning peak, since queues do form at the plaza. Boston's MPO estimates that a demand of 5400 vph occurs on this section of roadway.[41] This will be considered in the analysis for ETC installation and future year predictions.

To be complete, the non-dominant flow direction (i.e. not the peak direction) should be considered. Since ten lanes are open in the dominant direction, five are open in the non-dominant direction. These are two automatic and three manual lanes as shows in Table 6.3.

[40] Massachusetts Turnpike Toll Audit Department, 4/4/96 Hourly Counts
[41] Central Transportation Planning Staff, "Traffic Volumes on Limited-Access Highways Radiating from Downtown Boston", February, 1995.

Table 6.3 **Capacity of MassPike Plaza 19, East or West,** **-5 lanes in non-dominant direction**		
number/type of lane	capacity per lane (vph)	total capacity (vph)
3 manual lanes	465	1395
2 ACM lanes	550	1100
Total Capacity		2495

Fortunately, the non-dominant peak transactions for the morning rush hour is around 2200 vph.[42] Therefore the non-dominant flow direction will not have any queues since the capacity is more than the non-dominant peak transactions. (This has also been confirmed by casual observation.)

From the information given thus far, it can be concluded that the dominant flow direction is the bottleneck of the plaza, to which most of the following analysis should be dedicated. The non-dominant direction should have no queues.

6.2 Current Demand and Electronic Toll Collection Configuration

Long before ETC is installed at this plaza, it is necessary to determine what sort of lane configuration should be put into place with ETC. Since the dominant flow direction is the capacity constraint for this plaza, the peak hour dominant demand will determine the lane configurations under ETC. This peak hour occurs during the morning rush hour. The evening peak is spread out further, with lower demands.

When ETC is considered, a certain number of lanes must be converted to ETC use. According to the design characteristics in Table 3.1, if peak demand is around 5000 vph (the actual peak demand in this situation is around 5400 vph as noted earlier), dedicated ETC lanes

[42] ibid.

should be considered. Also, for this analysis, an ETC market demand of 20% during peak hours will be assumed. (From the case studies in Chapter 4 and other sources on ETC penetration rates, 20% is a reasonable estimate for an ETC system which is about two years old at a large plaza like this one. Other estimates may be achieved through patron surveys which could then be used in an analysis. Nonetheless, the analysis techniques given would be the same.) Figure 3.2 suggests that at 20% ETC penetration, three lanes could be eliminated from the plaza. However, for reasons which will become apparent, a more conservative estimate of two lanes eliminated is chosen. This leaves eight lanes to configure.

Given that the peak demand for ETC in this example is 20%:

5400 vph demand * 20% ETC penetration = 1080 vph ETC market

Therefore 1080 vph will travel through the ETC lane during the peak hour. Hence, one dedicated ETC lane, with a capacity of 1200 vph, should handle all of the ETC traffic. The remaining seven lanes will be divided into four ACM lanes and three manual lanes (one manual lane converted to ETC and one manual lane converted to ACM.) The new capacity is given in Table 6.4 as 4795 vph, which is much smaller than the earlier estimate of 4905 vph. This capacity is further reduced by the fact that only 1080 vph use the ETC lane in the peak hour, leaving 120 vph excess capacity in the ETC lane. Since only ETC customers can use this lane, the actual total available capacity drops to 4675 vph. This is obviously far too low and does not even meet the current capacity situation. Therefore, it is unwise to use the information in Figure 3.2 for anything but a general starting point. A more in-depth analysis, as is given below, should be performed. (The inaccuracy of Figure 3.2 is likely due to the lower processing rates for the lane types assumed to create Figure 3.2. Thus, more lanes can be eliminated, since they process fewer vehicles.)

In the case of the plaza under analysis, the current capacity of 4905 vph is clearly low (see Table 6.2), especially if elimination of queues is desired. By choosing a dominant direction

Table 6.4 **Capacity of MassPike Plaza 19, East or West,** **-8 lanes open in dominant direction, 1 dedicated ETC lane**		
number/type of lane	capacity per lane (vph)	total capacity (vph)
3 manual lanes	465	1395
4 ACM lanes	550	2200
1 ETC dedicated lane	1200	1200
Total Capacity		4795

lane configuration of ten lanes broken into five manual lanes, four ACM lanes, and 1 dedicated ETC lane, a capacity of 5605 vph is achieved as shown in Table 6.5 (assuming the 20% ETC penetration rate given above.) This would most likely be the best solution for implementation of ETC under current demand. Note that no lanes were eliminated but the capacity increased from 4905 vph to 5605 vph without physical expansion. The demand of 5400 vph is thus fulfilled by this ETC arrangement.

Table 6.5 **Capacity of MassPike Plaza 19, East or West,** **-10 lanes open in dominant direction, 1 dedicated ETC lane**			
number/type of lane	total capacity (vph)	total demand (vph)	available capacity (vph)
5 manual lanes (465 each)	2325	***	2325
4 ACM lanes (550 each)	2200	***	2200
1 ETC dedicated lane (1200)	1200	1080	1080
Total Available Capacity			5605

Note that the total demand for manual and ACM lanes (***) is not included. The demand at these lanes is assumed to be mixed correctly for achieving maximum capacity out of both types of lanes. However, if the number of ACM patrons is lower than 2200 while excess demand exists for the manual lanes, a lower overall capacity will be achieved.

For the non-dominant direction, those with ETC tags will have to have an ETC lane installed in the non-dominant direction. The demand, however, is not high enough for a dedicated ETC lane:

2200 vph * 20% ETC market = 440 vph ETC in non-dominant direction

Hence, a mixed ETC/ACM lane is installed. The new capacity (2730 vph) exceeds the demand (2200 vph) by 530 vph, as shown in Table 6.6. Thus, if the market permits, one manual lane may be closed (capacity is then 2265 vph) while still reaching demand or one ACM lane may be closed (capacity is then 2180 vph) with some minor queuing.

Table 6.6

Capacity of MassPike Plaza 19, East or West,
-5 lanes open in non-dominant direction, 1 mixed ETC lane

number/type of lane	total capacity (vph)	total demand (vph)	available capacity (vph)
2 manual lanes (465 each)	930	***	930
2 ACM lanes (550 each)	1100	***	1100
1 ETC/ACM mixed lane (700)	700	440 ETC 260 ACM	700
Total Available Capacity			2730

*** indicates demand consistent with manual/ACM lane configuration

In total, there will be an major increase in service for the dominant direction (from 4905 vph to 5605 vph), and no decrease or a minor decrease in service for the non-dominant direction (from 2200 vph to 2180 vph if an ACM lane is eliminated). The overall toll plaza will likely function much better. The lane configuration would now look like Figure 6.3. (The right hand lane may be closed for the non-dominant direction, saving some costs, as noted in the figure.)

Note that Figure 6.3 is ideally laid out, with all manual lanes being to the right, all ACM lanes in the center, and all ETC lanes to the left for both the dominant and non-dominant direction at both peaks during the day. This is the recommended set-up to avoid channelization problems. However, it does require six more ACM's and four ETC readers to be installed.

Since most toll facilities are experiencing increasing traffic, it is unlikely that the above scenario would be implemented, since it does not increase capacity in anticipation of future demand increases. However, it does show the possible trade-off between investment in ETC equipment and the increased capacity with one fewer manual lanes open. For a complete cost example of this type of lane elimination, see Chapter 7.

6.3 Capacity Analysis Under Future Demand

For capacity analysis for future years, assume the growth rate is around 1% per year, which is reasonable for the Boston Metropolitan area, based on prior growth.[43] This would indicate a 10% increase for a 10 year future analysis. Since total processing in the current year is approximately 4900 vph and queues still exist, it can be assumed that demand (the number of patrons desiring to pass through the toll plaza during the peak hour) is even greater than this. The MPO for Boston estimates 5400 vph for the Eastbound morning peak, as mentioned earlier.[44] Assuming a 10% growth rate, the peak hour demand rises to 6000 vph from 5400 vph ten years in the future. Clearly, the current plaza arrangement will not handle this type of traffic without major delays since the capacity is around 4900 vph. The capacity needs to be increased by over 1000 vph to meet the demand. This would require the installation of two additional physical lanes, either one manual and one ACM, or two ACM, as shown in Table 6.7.

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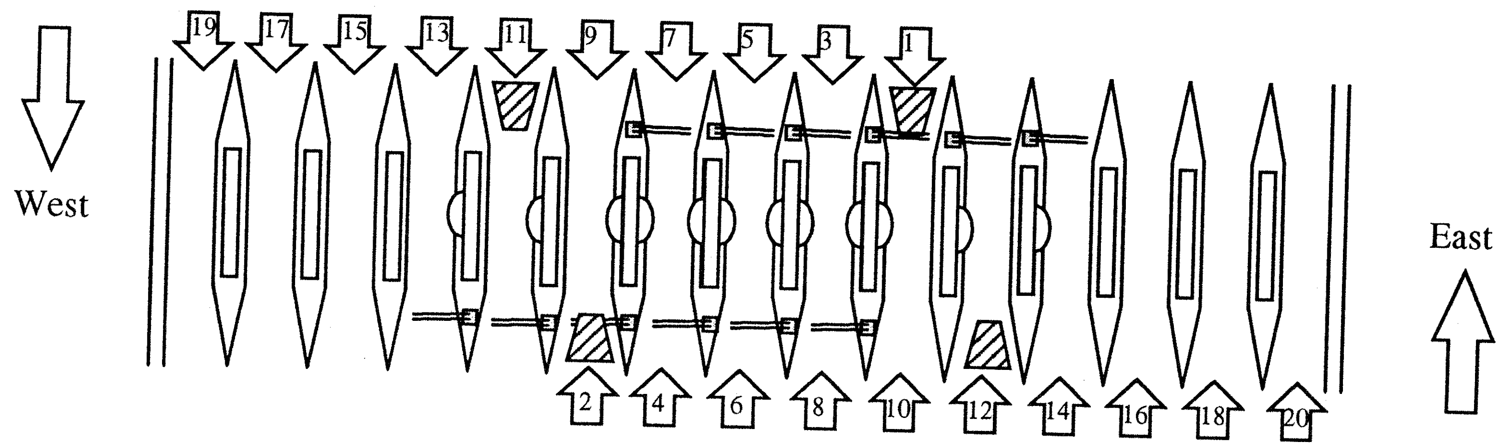
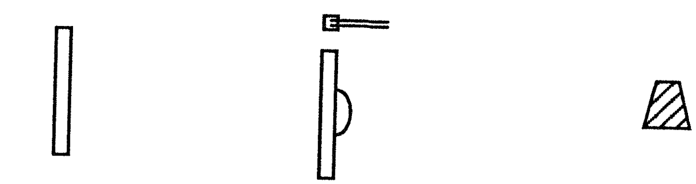
[43] Based on average weighted daily traffic increasing from 40,000 in 1987 to 42,000 in 1992 as noted in "Traffic Volumes on Limited-Access Highways Radiating from Downtown Boston", Central Transportation Planning Staff, February, 1995.
[44] Central Transportation Planning Staff, "Traffic Volumes on Limited-Access Highways Radiating from Downtown Boston", February, 1995.

Figure 6.3: ETC Configuration, Plaza 19, Massachusetts Turnpike



Key:

Lanes	15-20	Manual
Lanes	13-14	Manual or ACM
Lanes	11-12	Manual or Dedicated ETC
Lanes	3-10	Automatic Coin
Lanes	1-2	Dedicated ETC



Six ACM machines have been added (lanes 3-8). For the eastbound peak, lane 2 is dedicated ETC, lanes 4,6,8,10 are ACM, and lanes 12,14,16,18,20 are manual. Lanes 1,3,5,7,9 are reversed (operating in eastbound direction), lane 11 is ETC/ACM mixed, lane 13 is ACM, and lanes 15 and 17 are manual. Lane 19 is closed since it is not needed. The configuration reverses for the westbound peak. Note that this arrangement also optimizes the channelization before the plaza. Namely, the manual lanes are always to the far right, the ACM lanes in the middle, and the ETC lane on the far left for both the dominant and non-dominant direction, simultaneously.

However, expansion of the plaza in this manner would be difficult since it is in an urban, restricted growth area and building extra lanes is costly, (from $150,000 to $750,000 per lane plus equipment costs.)[45] Note also that the non-dominant direction traffic would increase from 2200 vph to 2420 vph (in 10 years), which is still lower than the capacity in that direction (2495 vph), thus no adjustments would be necessary for the non-dominant direction.

Table 6.7

Capacity of MassPike Plaza 19, East or West, 10 Year Future Forecast -12 lanes open in dominant direction (2 additional lanes constructed)

number/type of lane	capacity per lane (vph)	total capacity (vph)
7 manual lanes	465	3255
5 ACM lanes	550	2750
Total Capacity		6005

6.4 Capacity Analysis Under Future Demand with ETC

If an ETC program is put into place on the MassPike soon, provided there is good marketing and good patron response, it is a possibility that the ETC market penetration will have increased to 40% in 10 years (based on facilities using ETC for several years that currently have this level of ETC penetration rates and trends in ETC penetration given in papers on the subject.[46]) Thus, assuming a 40% ETC penetration rate, the ETC patron demand will be:

6000 vph demand * 40% ETC penetration = 2400 vph ETC demand

Clearly, one dedicated ETC lane will not be sufficient, as in the current demand ETC analysis. If two dedicated lanes are installed, their capacity would be 2400 vph. In addition, if there are four manual and four ACM lanes, the capacity of these lanes is given in Table 6.8 as 6460 vph.

[45] NCHRP194, page 22.
[46] James Griffin, David Boss, and James Johns, "Trends In ETC Participation", *IBTTA International ETTM Symposium*, September, 1995.

Table 6.8 **Capacity of MassPike Plaza 19, 10 Year Future Forecast -10 lanes open in dominant direction, 2 dedicated ETC**		
number/type of lane	capacity per lane (vph)	total capacity (vph)
4 manual lanes	465	1860
4 ACM lanes	550	2200
2 Dedicated ETC lanes	1200	2400
Total Capacity		6460

Hence, the new capacity of the plaza will have increased to meet future demand (6000 vph), without expanding the number of physical lanes. The ETC lanes are running at full demand (2400 demand, 2400 capacity), which implies there is no reduction in capacity due to ETC market penetration. Given that the ETC lanes are running at their peak capacity, an ACM/ETC lane replacing an ACM lane might be considered if ETC usage rates are expected to increase in the near future to avoid delays on the ETC lanes.

In the non-dominant direction, traffic will have increased to a peak of 2420 vph, as noted above. The ETC proportion of this is:

2420 vph demand * 40% ETC penetration = 968 vph ETC demand

Here, perhaps one dedicated ETC lane is in order, since 968 ETC vehicles in an hour would crowd a mixed ETC/ACM lane. Assuming one dedicated ETC lane, the capacity would be 2998 vph (see Table 6.9) which more than satisfies the demand requirements of 2420 vph. Therefore, one lane could be closed in the off peak direction again, either an ACM lane or manual lane, depending on the market share.

Assuming one manual lane is closed, see Figure 6.4 for a 10 year future lane configuration chart. Notice that a total of six ETC readers and four additional automatic coin lanes must be

Table 6.9

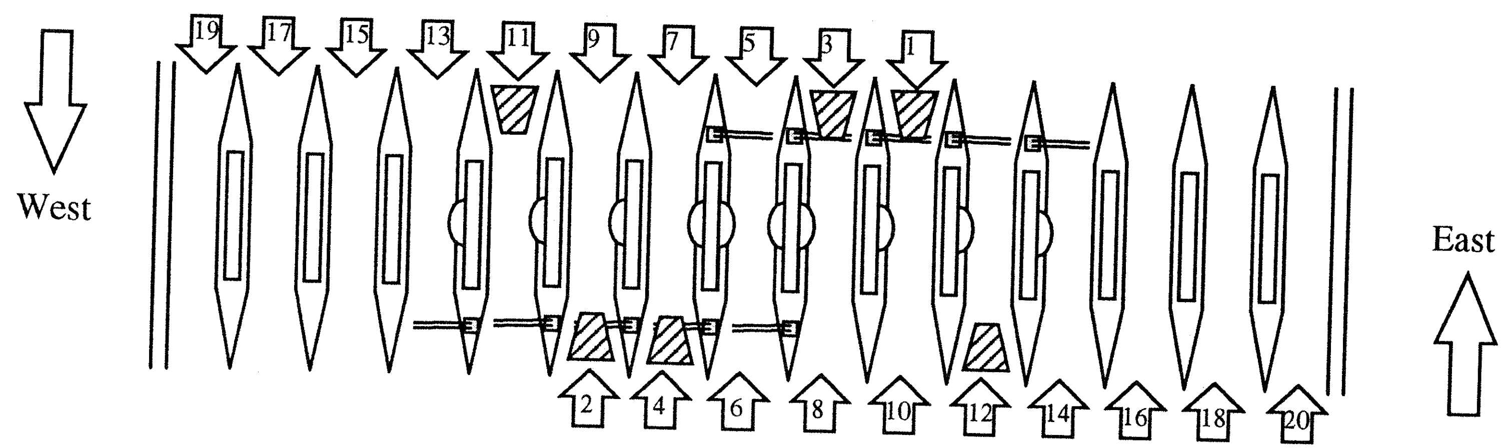
Capacity of MassPike Plaza, 10 Year Future Forecast
-5 lanes open in non-dominant direction, 1 dedicated ETC lane

number/type of lane	total capacity (vph)	total demand (vph)	available capacity (vph)
2 manual lanes (465 each)	930	***	930
2 ACM lanes (550 each)	1100	***	1100
1 ETC dedicated lane (1200)	1200	968	968
Total Available Capacity			2998

*** indicates demand consistent with manual/ACM lane configuration

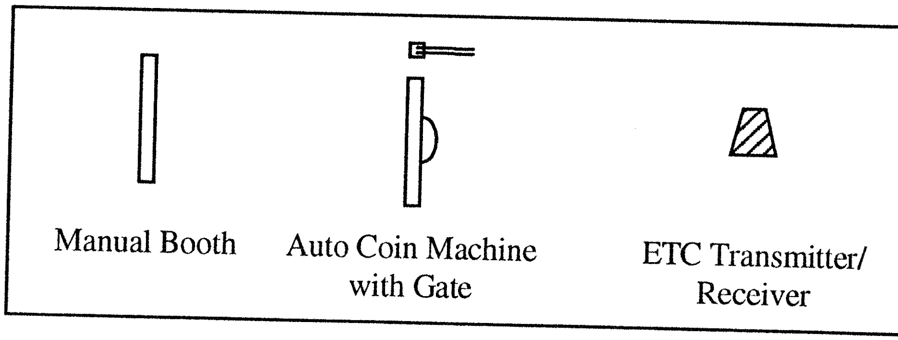
installed. (Over the previous ETC configuration, only the small change of lanes 4 and 3 being converted to dedicated ETC has taken place.) However, the total physical size of the plaza is unchanged while capacity meets future demand. Without the capacity improvements provided by ETC, two physical lanes would have to be added to the plaza to achieve the same throughput.

Figure 6.4: 10 Year Configuration, Plaza 19, Massachusetts Turnpike



Key:

Lanes	15-20	Manual
Lanes	13-14	Manual or ACM
Lanes	11-12	ACM or Dedicated ETC
Lanes	5-10	Automatic Coin
Lanes	1-4	Dedicated ETC



Four ACM machines have been added (lanes 5-8). For the eastbound peak, lanes 2 and 4 are dedicated ETC, lanes 6,8,10,12 are ACM, and lanes 14,16,18,20 are manual. Lanes 1,3,5,7,9 are reversed (operating in eastbound direction), lane 11 is dedicated ETC, lane 13 is ACM, and lanes 15 and 17 are manual. Lane 19 is closed since it is not needed. The configuration reverses for the westbound peak.

6.5 Queuing Analysis Under Current Demand

Utilizing information from the audit department of the Massachusetts Turnpike and the Boston MPO, a queuing model for current demand can be developed. Since the current capacity of the plaza in the non-dominant direction exceeds the demand, only the dominant direction will be considered.

The actual capacity of the plaza is about 4900 vph and the demand is about 5400 vph during the peak, as noted earlier. (Again, an approximation to a round number of 4900 vph has been made, instead of using the 4930 vph reported by MassPike. However, given the roughness of the approximations made for the queuing analysis, this will not have a significant effect.) The mix of lanes is assumed to match the mix of vehicles approaching the toll plaza. (More precisely, there are not more manual patrons than there are lanes to cover them. However, there can be more exact change patrons than ACM lanes since these patrons can also use manual lanes.)

Using transaction records from the Massachusetts Turnpike, total transactions by hour can be determined. Assuming the demand for the plaza only exceeds capacity during the peak hour, 7:00 - 8:00 a.m., the arrival rate for this hour is adjusted up to 5400 vph. For the remainder of the hours, the capacity is assumed higher than the demand, and total transactions for each hour equals the demand for that hour. Then the application of the queuing model developed in Chapter 5 with the current maximum capacity of 4900 vph will result in the maximum queue, total wait time, average wait time, and maximum wait time as shown in Table 6.10.

Here the average wait for those who wait is fairly short, about 3.3 minutes, and the maximum wait is also fairly short, about 6 minutes. Figure 6.5 shows a plot of the queuing. Since there is very little wait time, the arrival and departure lines are right on top of each other, only splitting at the 8:00 hour. The plaza, under these conditions, seems to operate well.

Table 6.10

Queuing Model Spreadsheet Outputs for MassPike Plaza 19 Morning Peak Direction, Current Conditions

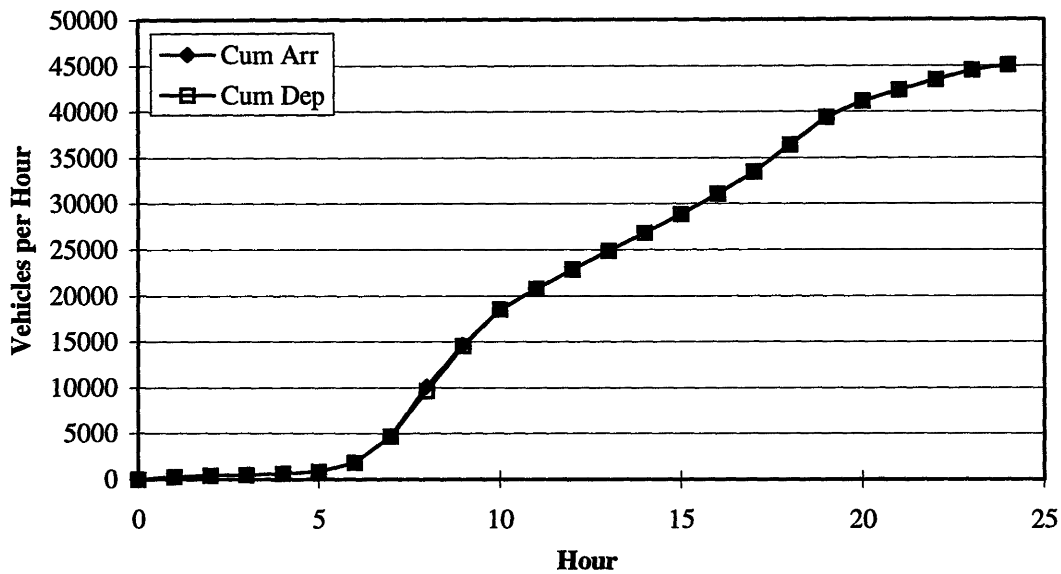
Hour	Arrivals (vph)	Cum Arr (vehicles)	Departures (vph)	Capacity Shortage (vph)	Q Length (vehicles)	Cum Dep (vehicles)	Tot Delay (vehicle hours)
0		0	4900		0	0	0
1	264	264	4900	-4636	0	264	0
2	162	426	4900	-4738	0	426	0
3	94	520	4900	-4806	0	520	0
4	111	631	4900	-4789	0	631	0
5	208	839	4900	-4692	0	839	0
6	997	1836	4900	-3903	0	1836	0
7	2875	4711	4900	-2025	0	4711	0
8	**5400**	10111	4900	500	500	9611	250
9	4532	14643	4900	-368	132	14511	566
10	3851	18494	4900	-1049	0	18494	574
11	2255	20749	4900	-2645	0	20749	574
12	2083	22832	4900	-2817	0	22832	574
13	2047	24879	4900	-2853	0	24879	574
14	1936	26815	4900	-2964	0	26815	574
15	2059	28874	4900	-2841	0	28874	574
16	2170	31044	4900	-2730	0	31044	574
17	2439	33483	4900	-2461	0	33483	574
18	2902	36385	4900	-1998	0	36385	574
19	2978	39363	4900	-1922	0	39363	574
20	1803	41166	4900	-3097	0	41166	574
21	1119	42285	4900	-3781	0	42285	574
22	1155	43440	4900	-3745	0	43440	574
23	1039	44479	4900	-3861	0	44479	574
24	591	45070	4900	-4309	0	45070	574

Total Wait Time: 574 veh hrs — Average Wait Time: .76 min.

Maximum Wait: 6.1 min. — Maximum Queue: 500 veh.

Average Wait Time For Those Who Must Wait: 3.3 min.

Figure 6.5
Queuing Graph for MassPike Plaza 19 Under Current Demand



This queuing situation can be compared to the queuing under the ETC configuration suggested in Figure 6.3 whose capacity reaches the demand of 5400 vph. A queuing analysis here is not necessary. All wait times and queues will be zero, which is an improvement in the level of service at this plaza. Under the proposed ETC system, queues will be eliminated and time will be saved by patrons (both ETC and non-ETC.)

6.6 Queuing Analysis Under Future Demand

For a 10 year forecast, the demands throughout the day are estimated to increase by 10% as noted above. By performing a similar queuing analysis with these future demands and the current non-ETC plaza configuration, the results in Table 6.11 can be obtained.

Here maximum wait time has doubled over the current year queuing analysis, and the average wait time for those who must wait has tripled. This kind of wait (10 minutes) on a daily basis is probably unacceptable in terms of the level of service characteristics at which the toll

Table 6.11

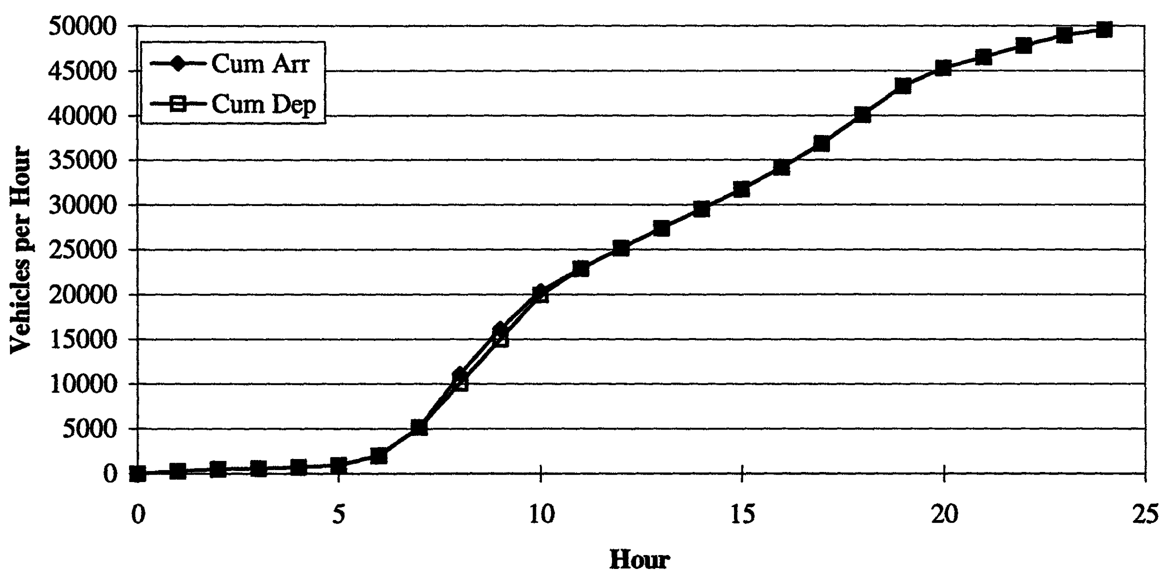
Queuing Model Spreadsheet Outputs for MassPike Plaza 19
Morning Peak Direction, 10 Year Future Conditions

Total Wait Time	2440 veh hrs	Average Wait Time	2.9 min.
Maximum Wait	13 min.	Maximum Queue	1125 veh.
Average Wait Time For Those Who Must Wait:		9.4 min.	

authority wishes to operate. (This is one of the most useful aspects of the queuing model. It shows that something will need to be done about the capacity situation by the ten year time frame.)

Figure 6.6 shows the queue plot for this situation, where no expansion takes place or ETC system is installed.

Figure 6.6
Queuing Graph for MassPike Plaza 19 Under Future Demand,
No Change in Plaza



This figure shows the increased wait times since the gap between the arrivals and departures lines (total wait time) has increased since the current year queuing analysis graph shown in Figure 6.5

If the ETC system is installed as described in the previous section, the capacity will increase to 6460 vph, and there will be no queues, since the maximum demand in the future is 5940 vph.

In summary, the effect of the proposed ETC system 10 years in the future is even more pronounced as even longer queues are eliminated.

6.7 Conclusions for Massachusetts Turnpike Plaza 19

The preceding arguments have shown the available capacity and queuing characteristics in current and future demand situations both with and without ETC systems in place.

Table 6.12 shows a summary of the capacity analyses performed.

For the current year, it is possible to see that eliminating lanes when ETC is installed may be possible, with increases in service. However, for a ten year future forecast, demand will outstrip capacity by a large margin, thereby suggesting increasing capacity and new lanes. Alternatively, the capacity model shows how necessary capacity can be added using ETC without adding any physical lanes for the future year analysis.

Table 6.12 MassPike Plaza 19 Capacity Summary						
Situation/Lane Mix	Manual	ACM	ETC/ ACM	Dedicated ETC	Demand (vph)	Capacity (vph)
Current Year - Current Configuration - 15 lanes						
-Dominant	7	3	0	0	5400	4905
-Non-Dominant	3	2	0	0	2200	2495
Current Year - ETC Configuration - Possible 1 manual lane closed - 14 lanes						
-Dominant	5	4	0	1	5400	5605
-Non-Dominant	2	2	1	0	2200	2730
Ten Year Forecast - Current Configuration						
-Dominant	7	3	0	0	6000	5400
-Non-Dominant	3	2	0	0	2420	2495
Ten Year Forecast - Expanded Plaza - 2 new lanes built						
-Dominant	7	5	0	0	6000	6005
-Non-Dominant	3	2	0	0	2420	2495
Ten Year Forecast - ETC Configuration - Possible 1 ACM lane closed - 14 lanes						
-Dominant	4	4	0	2	6000	6460
-Non-Dominant	3	1	1	1	2420	2998

From the queuing model, it was possible to determine the current wait times and queue lengths. These should be calibrated against actual data, but such information was not available for this research. Then, for future year demands, the wait times and queue lengths under the current capacity were determined. Finally, for increased capacity as suggested by the capacity model, wait times and queue lengths can be determined, which in this case are zero. Table 6.13 gives a summary of the queuing statistics under the different demands and configurations.

Table 6.13 MassPike Plaza 19 Queuing Summary		
Situation	Max. Wait (minutes)	Ave. Wait* (minutes)
Current Year - Current Configuration	6.1	.76
Current Year - ETC Configuration	0	0
10 Year Forecast - Current Configuration	2.9	13
10 Year Forecast - Expanded Configuration	0	0
10 Year Forecast - ETC Configuration	0	0

*for those who do wait

Thus it is easy to see the effects of the implementation of an ETC system. Queues can be virtually eliminated for current and future year demand levels without costly expansion of the plaza.

A note about this MassPike analysis:

The analysis given here is for illustrating the use of the models developed in Chapter 5 for an actual toll plaza. However, many characteristics of the toll lane configurations have not been examined, for instance ETC equipment costs and operations costs. In addition, the benefits shown here are strictly given from a capacity and queuing standpoint. However, many other possible benefits for the MassPike and its patrons exist. See Chapter 3 for a complete list of costs, benefits, and concerns associated with ETC systems. A more complete analysis of an actual toll system, including costs, benefits, and concerns is given in Chapter 7.

Chapter 7

Application to Puerto Rico

The goal of this chapter is to present a "first approximation" analysis of a real toll facility, including possible introduction of ETC, from qualitative, capacity, queuing, and cost stand points. The facilities used in this study are the toll expressways in the Commonwealth of Puerto Rico.

First, a general description of the tollways will be followed by a qualitative analysis of the tolling aspect of these roadways and possible introduction of Electronic Toll Collection. Next, using methods presented in Chapter 5, a capacity analysis of the most congested plaza in Puerto Rico (Buchanan plaza) under current conditions and future demand will be presented, with suggested lane configuration changes and conversions to ETC. Then, a queuing analysis of the Buchanan Plaza will be made, with current and projected usage. Both the capacity and queuing analysis will make use of 2010 traffic forecasts with and without the introduction of Tren Urbano, a rail transit line proposed for Puerto Rico. Finally, a cost analysis of operations at the same plaza will be made under current conditions and with ETC installed in order to give a real example of the costs involved with ETC systems. General conclusions and recommendations follow.

7.1 General information

Situated southeast of Miami, the island of Puerto Rico is home to approximately 3.6 Million people. The island is about 100 miles long (east to west), and 35 miles wide (north to south.) Its largest metropolitan area, the San Juan Metropolitan Region (SJMR), has about 1.3 million inhabitants.[47] The city is located on the northern coast. (See Figure 7.1 for map.) Most of

[47] Puerto Rico Highway and Transportation Authority, *Puerto Rico's Tren Urbano - Putting Transit Innovation On-Track for the 21st Century*, Government of Puerto Rico pamphlet, 1993.

the major commerce, cultural, educational, transportation, and governmental activities are located in San Juan.

In the past several years the SJMR has been experiencing rapid growth in trip-generation and trip-making, without consequent increases in facilities, such as roadways. The travel demand patterns are causing large daily backups and lengthy congestion throughout the region. Keeping this in mind, the government has decided to overhaul the transit system, and add a new rail rapid transit line. This project, known as Tren Urbano (or Urban Train), is well underway with initial construction expected to begin in 1996. Tren Urbano will be a 12 mile transit line extending from the primary commercial area in San Juan, westward to the municipality of Bayamon. It is expected to carry 115,000 trips daily.[48] In addition to building the transit line, the project encompasses many other aspects of transportation from improved bus services to ITS applications, such as Electronic Toll Collection.

There are two main expressways serving the island: PR-22 "De Diego" runs from San Juan west along the north shore of the island to Arecibo, (the first part of which parallels the proposed Tren Urbano alignment); and PR-52 "Luis A. Ferre" which runs south from San Juan to the southern coast and then west to Ponce. (PR is the route designation for government roads in Puerto Rico.) A third expressway is being built, PR-53, which splits from PR52 when it reaches the southern shore in Salinas, and runs east and north along the southern and eastern shores towards San Juan. However, since PR-53 is only partially completed for use in some areas, it will not be included here. In addition, a private/public partnership project, Puente Teodoro Moscoso - a bridge connecting the SJMR business district to the international airport, has utilized some electronic toll collection, but will not be considered here.

The expressways are considered to be the best way to travel throughout the island. They are generally four lane, divided, limited access highways similar to Interstate Highways in the rest of the U.S. All other roads on the island are often two lane with inadequate capacity and

[48] ibid.

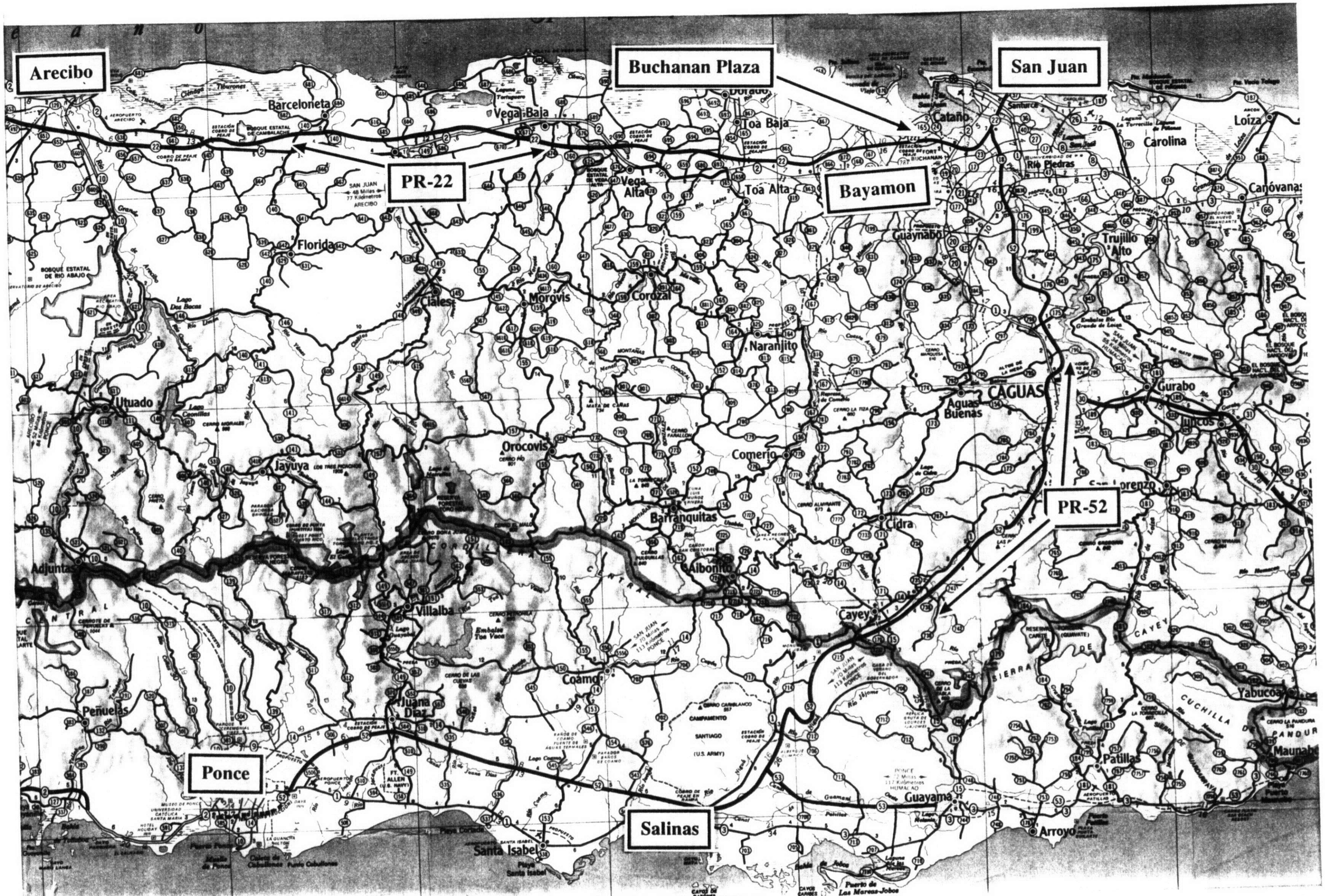


Figure 7.1: Puerto Rico - Cities and Tollways

alignment. Thus, there is a great demand for travel along the length of both roadways by those needing to travel to and from San Juan. Outside of the SJMR, travel is predominantly limited to non-commuter trips. In the San Juan Metropolitan Region (SJMR), like any other major city's expressways, the expressways are used for commuting as well as less frequent trips for other, non-work purposes.

Both PR-22 and PR-52 are barrier-type toll systems, with most plazas being on the main line of the road. Table 7.1 shows the vital statistics for both roadways. The number of stops required on these expressways is extraordinarily high, up to 6 stops for tolls on 48 miles in the case of PR-22. Although the plaza density is less than most of the case studies in Chapter 4, it is important to point out that most of the plazas in the case studies are ramp plazas, not barrier plazas. Those traveling on these two roads in Puerto Rico must stop and pay a toll at every plaza. Plaza sizes vary from 6 lanes to 24 lanes for barrier plazas, and 3 or 4 lanes for ramp plazas.

Table 7.1

Puerto Rican Expressways

Road	Length	Number of Plazas	Average Miles Between Plazas
PR 22	48 miles	6 (all barrier)	8
PR 52	60 miles	8 (5 barrier, 3 ramp)	12

Source: Map of Primary Roads of Puerto Rico, Department of Transportation and Public Works, Puerto Rico, December 1993.

The toll at the plazas for autos is very low, ranging from \$.25 to \$.65.[49] Hence great use is made of automatic coin collection machine lanes (ACM's). Credit card payments are also allowed as a customer convenience.

Although newer manual and automatic coin collection lanes have been installed in many places on the tollways, ETC may be a viable toll collection for this situation. Utilizing information presented thus far, a "first draft" analysis of the possibilities of ETC for Puerto Rico is given below.

7.2 Electronic Toll Collection - Qualitative Aspects

There are several key qualitative factors to consider when ETC is proposed for the expressways in Puerto Rico.

First, the frequency of plazas along the expressways is inconvenient for those traveling the length of the roadway. Several stops are required and exact change is often used at each plaza. Installation of ETC could help patrons by speeding up toll collection and allow non-stop passage through the toll plazas, decreasing the total trip time. Also, ETC could eliminate the need to carry large amounts of change for these trips.

For those traveling in the SJMR, the tollways are not as inconvenient on a per trip basis since usually only one, and sometimes two payments are needed in each direction. However, on a daily basis, this inconvenience can add time and cost to trips. Exact change is often used for these tolls also and the congestion at the plazas causes long queues. Levels of service are very low. Again, ETC could be a more efficient payment system for patrons, as well as help reduce queuing at toll plazas.

Another benefit in application of ETC would be in revenue protection, if adequate enforcement/security systems are installed. In the last few years, gate arms were installed on most ACM machines on the expressways. It was found that the toll revenue increased dramatically after the installation of the gates, without a corresponding increase in traffic. However, patrons still try to evade tolls by short changing the ACM machines, riding close to autos in front of them, charging gate arms, etc.[50] ETC would help to secure the revenue flow

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[49] Wilfredo Jirau Toledo, Director, Area Administration of Expressways, Puerto Rico Highway and Transportation Authority, Puerto Rico, May 1, 1995.
[50] Conversation with Freya Toledo, Puerto Rico Highway and Transportation Authority, January, 1996.

from the roadways with the added benefit of reducing cash handling, which can also cause loss of revenue due to theft, miscalculations, dropping of currency, etc.

The collection of tolls on the expressways is handled by an island-wide concession agreement. Unlike most U.S. toll facilities, the concession arrangement has the potential for allowing an outside "expert" on money handling and accounting to run the toll system, without major changes in the institutional structure already in place. As mentioned in Chapter 3 with regard to ownership arrangements, concessions may be preferable to authority operated collection since a concessionaire could put in the capital outlay for new toll collection equipment, including ETC, and is relatively impervious to law suits brought against public agencies. However, note that none of the case studies in Chapter 4 used this type of concession arrangement, suggesting that no precedent exists.

Another possible benefit of ETC for Puerto Rico would be in the area of commercial fleet operations. Commercial vehicle fleets, as mentioned in Chapter 3, frequently consider ETC to be a very helpful technology, allowing group billing of entire fleets of vehicles and reducing costly toll accounting. In addition, possible time savings from using dedicated ETC lanes is money saved for commercial operators.

Transit fleets and high occupancy vehicles (HOVs) such as publicos (private jitneys operated in Puerto Rico) could gain a great deal from the installation of ETC. For instance, if an exclusive transit/HOV lane is offered and toll collection is performed electronically, the amount of waiting time at tolls these vehicles experiences may be significantly reduced compared to the waiting time of each passenger in a private automobile. An example of this type of arrangement is the exclusive bus lane with ETC at the Lincoln Tunnel. (See Port Authority of New York and New Jersey case study in Chapter 4.) This time savings could help encourage people to take the bus, eliminating some vehicles on the crowded expressways in the San Juan area.

A final benefit of ETC for Puerto Rico may be in the use of congestion pricing for crowded areas of the expressways. Congestion pricing refers to the level of tolls being set on a roadway according to the level of congestion. During congested periods, the toll is raised to try and force patrons to switch to other modes, or switch time of travel to less congested periods, thereby lowering congestion, pollution, time losses, etc. Congestion pricing is generally not favored by the public since the exact amount of toll is not known before getting to the roadway and it is not known to the patron if they have enough money, there is an increase in cost to some patrons, and stopping for a congested toll plaza may reduce the time savings for which the patron is paying extra. ETC helps this situation since the amount of toll is taken off a pre-paid patron account, the patron need not worry about how much the toll might be. Also, waiting to pay tolls can be eliminated by the use of dedicated ETC lanes, giving more time savings benefit to the patron for the money spent on congestion prices.

From the above arguments, application of ETC in Puerto Rico looks favorable. There are, however, some qualitative concerns about use of ETC on the expressways.

First, although ETC could increase throughput at all plazas without expansion, it has the potential to cause increases in downstream congestion. This is especially true for two major plazas in the SJMR: Buchanan plaza, which is analyzed below, and Caguas Norte, which will not be analyzed. Due to an already severely congested roadway system in the San Juan area, backups after the toll plazas can frequently extend for a great distance. Increases in toll plaza flow may cause these backups to worsen, perhaps to the point of jamming the toll plaza itself, as travel demand increases along the roadways.

Another major concern is in the cost effectiveness of such systems. Automatic Coin Collection is a fairly inexpensive collection method on a per transaction basis. ETC, on the other hand, is often more expensive than automatic collection, but less expensive than manual collection. Since most collection on the expressways is automatic, ETC may cost more in the end. This aspect will be examined in the cost analysis.

A third concern is in the area of enforcement. As was noted in the Illinois State Toll Highway Authority case study in Chapter 4, enforcement can be an issue with ETC lanes. Conversations with observers of toll collection in Puerto Rico have revealed that toll evasion is fairly common on the island, as noted earlier. In addition, the only installation of ETC in Puerto Rico, on the Moscoso Bridge (an airport connector), has experienced toll evasion by patrons riding close to approved ETC vehicles and avoiding detection. Clearly a very precise and well enforced violation system would be necessary to cut down on toll evasion if ETC is installed on the expressways in Puerto Rico.

If exclusive lanes for high occupancy vehicles (HOVs) and transit with ETC are installed, another problem could occur similar to the Massachusetts Turnpike case study in Chapter 4. That is some HOVs, such as taxi cab drivers and publico operators may not be interested in using ETC. Taxi cab operators generally "cash-out" at the end of the day (tolls and fares) and the less than daily account resolution of ETC accounts may clash with this procedure. A similar situation exists for publico operators, who generally use the fares collected for one day on the same day for daily purchases. Money would have to be saved up in order to replenish the publico ETC account, instead of being spent each day. Also, taxicab drivers and publico drivers may have a hard time convincing patrons that a toll has been paid as they drive through the toll booth, not stopping to pay in cash.

Finally, considering that ETC is already used for a number of transactions on the Moscoso bridge, it may be necessary to coordinate accounting systems and ETC tags such that tags do not interfere with each other for the two systems. Alternatively, tags can be issued which can be used on both the Moscoso bridge ETC system and other ETC systems installed on the expressways, with account resolution taking place between the two systems.

The qualitative considerations given above look favorable, provided certain concerns are addressed, as noted.

7.3 Capacity Analysis

In this section, a capacity analysis of the plaza in Puerto Rico with highest average daily transactions, the Buchanan plaza on PR-22, will be presented. (See Figure 7.1 for location of Buchanan Plaza.) Techniques from Chapter 5 are used for this analysis.

First, a capacity analysis of the plaza with implications for future growth will show the capacity constraint problems at this plaza. Next, suggested improvements to the current plaza, including installation and utilization of an ETC system will be covered. Then, plaza capacity for the year 2010 will be examined, without and with ETC. Since forecasts for 2010 are available both with and without the Tren Urbano rail transit system, capacity analysis of both situations will be provided.

Utilizing lane and traffic information from the Highway and Transportation Authority in Puerto Rico, along with information from the San Juan Transportation Model, a capacity analysis for the Buchanan plaza can be performed. (The San Juan Transportation Model was developed for transportation planning in the SJMR and has been updated and improved for use in the planning for Tren Urbano.) This capacity analysis will be oriented towards the morning rush hour, when the peak demand for the plaza occurs, since the toll plaza capacity should be designed with the peak loading in mind. Therefore, unless otherwise noted, morning peak hour demands are given.

The Buchanan toll plaza is the plaza closest to the core of San Juan on PR 22. The plaza holds the distinction of being the largest and most congested toll plaza on the island. It consists of 24 lanes, most of which are automatic coin lanes. In 1995, average traffic through the plaza was 118,000 patrons daily.[51]

[51] Wilfredo Jirau Toledo.

7.3.1 1996 Current Year Capacity

For the dominant flow during the morning peak (inbound towards San Juan), the department of transportation reports that 14 lanes are typically open in the peak direction, 3 manual lanes and 11 automatic.[52] The high occurrence of automatic coin lanes (ACM lanes) is attributable to the low fare at this plaza, $.35 for class 1 passenger vehicles, which is collectable by ACM lanes.[53]

Table 7.2 shows the theoretical capacity of this plaza is 6700 vph. However, data is available confirming that the maximum processing rate reaches about 8000 vph during the peak hour, 7:00 - 8:00 AM.[54] This implies a much faster processing rate on average for the lanes and is probably due to the use of high speed gate arms and "lane-walkers" during the peak hours. Lane-walkers are stationed at automatic coin collection machines to take the toll payment from the patron and deposit it in the ACM basket while pre-empting the gate arm.

Table 7.2

Capacity of Buchanan Plaza - Current Year (dominant direction)

number/type of lane	capacity per lane (vph)	total capacity (vph)
3 manual lanes	400	1200
11 ACM lanes	500	5500
Total Capacity		6700

The patron does not have to wait for the ACM to process the toll and raise the gate, thus increasing capacity. The Puerto Rico Highway and Transportation Authority estimates all lanes (both manual and ACM) taken together process 570 vph on average.[55] Thus, it can be assumed that the ACM lanes process at levels greater than 570 vph, since manual lanes

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[52] Data from Puerto Rico Highway and Transportation Authority, June, 1996.
[53] Wilfredo Jirau Toledo.
[54] Data from Buchanan Plaza, Vehicles Processed During the Peak Hour, April 1996, Puerto Rico Highway and Transportation Authority, Puerto Rico.
[55] Letter from Wilfredo Jirau Toledo.

process about 400 vph. Figure 5.1 showed a processing rate of 800 vph for ACM lanes without gates. It can then be concluded that the actual capacity figure for ACM lanes at the Buchanan plaza is likely to be somewhere between 570 vph and 800 vph. If a figure of 620 vph is assumed, the maximum reported capacity of about 8000 vph is achieved. Table 7.3 shows the capacity using this new information.

Table 7.3

Capacity of Buchanan Plaza - Current Year - Corrected (dominant direction)

number/type of lane	capacity per lane (vph)	total capacity (vph)
3 manual lanes	400	1200
11 ACM lanes	620	6820
Total Capacity		8020

The "corrected" processing rate will be used for the remainder of the analysis, keeping in mind that lane-walkers must be used to achieve a capacity of 620 vph on an ACM lane.

To estimate the capacity shortfall of this lane configuration, information from the San Juan Transportation Model can be used. As mentioned, the model has been used during the planning stages for Tren Urbano, resulting in 1990 Study Year, 2010 No-Build Alternative (no Tren Urbano), and 2010 Build Alternative (with Tren Urbano) travel demands throughout the region.

The model shows a demand of 10,368 vph in the dominant direction during the peak hours (7:00 - 9:00) for 1990 at the Buchanan plaza.[56] For the year 2010 (without the building of Tren Urbano), the demand is estimated to be 12,696 vph. For 1996 (taken to be the "current year" analysis in this research), a linear interpolation produces a demand of 11,066 vph in the peak hours, for the dominant direction. Thus, when compared to the capacity given in Table 7.3, there is a shortfall of nearly 3,000 vph during the peak hours for the current year. This

[56] Cambridge Systematics, "Volumes on PR22, East of PR5", from SJMR Planning Model, June 17, 1996.

shortfall likely causes large backups at the toll plaza, with queues extending for a great distance during peak hours.

In the non-dominant direction during the peak, there are 10 lanes available. The transaction rates recorded in this direction for the peak hours (7:00-9:00 AM) average about 3120 vph.[57] Note that the 10 lanes are divided into 7 ACM and 3 manual lanes, giving a capacity of 5540 vph in the non-dominant direction using figures similar to Table 7.3. Thus the capacity in the non-dominant direction is never reached, and there are no queues. (It is probable that not all of the non-dominant direction lanes are opened for the morning peak, only those which are necessary to satisfy demand.) Excess capacity in the non-dominant direction is:

5540 vph capacity - 3120 vph demand = 2420 vph excess

One obvious solution to the dominant direction capacity shortage is to reverse excess non-dominant direction lanes, making them available for dominant direction usage. Four ACM lanes could be reversed, adding 2480 vph to the dominant direction, while still allowing good service to the non-dominant direction. (The non-dominant capacity compared to the demand will then be: 5540 vph -2480 vph = 3060 vph capacity; or 60 vph short of 3120 vph demand, which is a relatively small amount.) The new capacity in the dominant direction is shown in Table 7.4. The demand of 11,000 vph would still not be satisfied, but this arrangement would probably shorten queues at the plaza significantly. (See Section 7.5 below for queue and delay data under this configuration.) This modified configuration may not be in use at this time for two reasons. First, it may be too expensive to buy the extra equipment needed and hire labor for lane-walkers at the additional lanes. Secondly, by increasing the processing rate of the plaza, downstream traffic congestion may be worsened due to increased flow from the plaza, which is undesirable.

[57] Average of 7:00 - 9:00 AM weekday non-dominant processing records, first two weeks of May, 1996, from Puerto Rico Highway and Transportation Authority data.

Table 7.4 **Capacity of Buchanan Plaza - Current Year - Alternate Configuration (dominant direction, 4 reversed ACM lanes added)**		
number/type of lane	capacity per lane (vph)	total capacity (vph)
3 manual lanes	400	1200
15 ACM lanes	620	9300
Total Capacity		10,500

7.3.2 1996 Current Year ETC Design

Next, the capacity with an ETC system is analyzed for the current year. According to the design criteria discussed in Chapter 3, if ETC is being considered for this plaza, it is definitely a candidate for dedicated ETC lanes. As in the Massachusetts Turnpike Analysis in Chapter 6, assuming 20% ETC market share for a new ETC program:

11,066 vph demand * 20% ETC penetration = 2213 vph

This indicates that approximately two dedicated ETC lanes could be used in the dominant direction. Then the capacity would be 11,473 vph as shown in Table 7.5, assuming the ETC lanes are converted from ACM lanes, and four lanes were reversed from the non-dominant direction. The entire 11,066 vph demand is fulfilled, with approximately one manual lane's capacity to spare.

Table 7.5

Capacity of Buchanan Toll Plaza - Current Year - ETC Configuration (dominant direction, 4 reversed ACM lanes added)

number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
3 manual (400 vph)	1200	***	1200
13 ACM lanes (620 vph)	8060	***	8060
2 dedicated ETC lanes (1200 vph)	2400	2213	2213
Total available capacity			11,473

*** indicates demand consistent with manual/ACM lane configuration

A brief note about Express ETC lanes (with traffic operating at 55 mph):

Since the peak hour loading is well over 7,000 vph, the Buchanan plaza is a candidate for express ETC lanes according to Chapter 3 design criteria. However, it would be necessary to rebuild this plaza for express lanes. The current plaza is designed for vehicles which slow to a stop to enter a toll lane and pay a toll. In order to achieve non-stop express speeds through toll lanes, it is likely that an entire section of the center of the plaza would have to be removed, road geometry changes made, channelization and signage improvements put in place, and ETC equipment installed. Such major roadway geometry changes are likely to be extremely expensive, and the cost per express lane is likely to be many times that of each dedicated ETC lane. In addition, since the throughput of a dedicated ETC lane is 1600 vph as cited earlier, only one dedicated and one ETC/ACM mixed lane (with a maximum capacity of 700 vph) would be useful given the 2213 vph demand for ETC. The total ETC capacity would then be:

1600 vph dedicated + 700 vph ETC/ACM mixed = 2300 vph

Although this capacity is sufficient for the 2213 vph ETC demand, the same capacity can be gained through two dedicated ETC lanes. The ETC equipment costs will be approximately the same (since both situations require ETC equipment for two lanes), *leaving only the high civil construction costs of the express lanes as the difference between the two scenarios. Thus express ETC lanes are not considered for this analysis.*

There are 6 lanes remaining to configure for the non-dominant direction. In the non-dominant direction, with 20% ETC market share for the current year:

3070 vph demand * 20% ETC penetration = 614 vph ETC demand

Thus, one ETC/ACM mixed lane (with a capacity of 700 vph or greater) should be installed in the non-dominant direction, if an ETC program is put into place. The remaining five lanes will be configured as 3 manual and 2 ACM lanes, which is how they were configured originally.

As shown in Table 7.6, the non-dominant capacity is now 3140 vph, satisfying the 3120 vph demand. No queues will form.

Table 7.6

Capacity of Buchanan Toll Plaza - Current Year - ETC - Non-dominant Direction (non-dominant, 4 reversed ACM lanes subtracted)

number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
3 manual (400 vph)	1200	***	1200
2 ACM lanes (620 vph)	1240	***	1240
1 mixed ETC/ACM (700 vph)	700	614 ETC 86 ACM	700
Total available capacity			3140

*** indicates demand consistent with manual/ACM lane configuration

In summary, from the current year capacity analysis, it is easy to see that the Buchanan plaza is very short on capacity in the dominant direction. Some capacity can be added by reversing under utilized non-dominant direction lanes, with the remainder of the needed capacity provided by the increases available from ETC lanes and a strongly marketed ETC program.

Expansion of the plaza beyond 24 lanes is not necessary under the ETC configuration just described in order to reach current demand levels, and thus construction costs for more physical lanes can be avoided.

7.3.3 2010 No Build Alternative (for Tren Urbano) Capacity Analysis

Although the analysis for 1996 shows some major changes that can be made to increase capacity at the Buchanan plaza, it is likely that one would want to plan for the future, not for the current year. This is especially true if a large capital investment is involved (such as ETC or ACM equipment, or additional physical lanes.)

In the situation where Tren Urbano does not get built (i.e. No Build Alternative), the peak hour demand for the plaza increases to 12,696 vph for the morning rush hour in 2010, again outstripping the capacity of the plaza in the dominant direction.[58] The extra capacity needed is:

12,696 vph demand - 8020 vph capacity = 4676 vph.

To reach this capacity, nearly eight more ACM lanes with lane-walkers would be required in the dominant direction. Some of these lanes could be obtained from reversing non-dominant direction lanes as in the current year analysis. In order to determine how many lanes are available for reversing, it is necessary to look at the non-dominant direction peak demand for 2010. The non-dominant peak increases to 3,386 vph in the 2010 No Build Alternative.[59] The current capacity in the non-dominant direction is 5540 vph as noted earlier. Excess capacity in the non-dominant direction is:

5540 vph capacity - 3386 vph demand = 2154 vph excess

[58] Cambridge Systematics.
[59] ibid.

Hence, approximately 3 ACM lanes can be reversed to serve the dominant direction, with 7 lanes (4 ACM and 3 manual) in the non-dominant direction. This still leaves the dominant direction 5 ACM lanes of capacity short. Adding 5 physical lanes to an already very large plaza is likely to be very expensive and cause many operational problems, owing to the shear size of the plaza. To the author's knowledge, this would be the largest toll plaza in the United States at 29 lanes. (Table 7.7 gives the dominant direction capacity for the fully expanded plaza.)

Table 7.7

Capacity of Buchanan Plaza - 2010 No Build - Expanded Plaza (dominant direction, 3 reversed ACM lanes added, 5 new ACM lanes added)

number/type of lane	capacity per lane (vph)	total capacity (vph)
3 manual lanes	400	1200
19 ACM lanes	620	11,780
Total Capacity		12,980

In the case that Tren Urbano does not get built and an ETC system is not put into place, the Buchanan plaza will need significant expansion to keep up with ever-increasing demand.

7.3.4 2010 No Build Alternative ETC Design

If ETC is installed soon (1996-1998 for instance) on the expressways, perhaps a market share of 40% could be reached by 2010 (based on similar facilities with similar participation rates that have been using ETC for several years and increasing penetration rates given in some publications.[60]) Then the ETC demand in the dominant direction will be:

12,696 vph demand * 40% ETC penetration = 5078 vph ETC demand

[60] James Griffin, David Boss, and James Johns, "Trends In ETC Participation", *IBTTA International ETTM Symposium*, September, 1995.

Roughly 4 dedicated ETC lanes and 1 ETC/ACM mixed lane are needed to fulfill this ETC demand. (Alternatively, three express ETC lanes plus 1 mixed ETC/ACM lane could also reach this capacity. However, as noted earlier, express ETC lanes would be very difficult and expensive to build at this plaza, and thus will not be considered at this time.)

The capacity with four dedicated ETC lanes and one mixed ETC/ACM lane is given in Table 7.8.

Table 7.8

Capacity of Buchanan Plaza - 2010 No Build - ETC Configuration (dominant direction, 4 reversed ACM lanes added)

number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
3 manual lanes (400 vph)	1200	***	1200
10 ACM lanes (620 vph)	6200	***	6200
1 mixed ETC lane (700 vph)	700	278 ETC 422 manual	700
4 dedicated ETC lanes (1200 vph)	4800	4800	4800
Total available capacity			12,900

*** indicates demand consistent with manual/ACM lane configuration

The demand of 12,696 vph is fully satisfied by the capacity. Note that four reversed ACM lanes are included in the table when compared to the original configuration.

This arrangement leaves six lanes of 24 for configuring the non-dominant flow. For the 2010 No Build Alternative, the morning non-dominant demand is 3,385 vph. Assuming again that 40% of this market is ETC:

3,385 vph demand * 40% ETC market = 1354 vph

This level of demand calls for one dedicated ETC lane and one ETC/ACM mixed lane. The total capacity available using this arrangement, along with one ACM lane and the original three manual lanes, is given in Table 7.9.

Table 7.9

Capacity of Buchanan Plaza - 2010 No Build - ETC - Non-dominant Direction (non-dominant, 4 reversed lanes subtracted)

number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
3 manual lanes (400 vph)	1200	***	1200
1 ACM lanes (620 vph)	620	***	620
1 mixed ETC lane (700 vph)	700	154 ETC 546 manual	700
1 dedicated ACM lanes (1200 vph)	1200	1200	1200
Total available capacity			3720

*** indicates demand consistent with manual/ACM lane configuration

Thus, the non-dominant demand of 3,385 vph is satisfied, with perhaps one manual lane to spare, which could be eliminated.

In total, the 2010 No Build situation can be handled by the current plaza in theory, provided a strong ETC program exists by that point. Unlike the non-ETC option, no additional lanes need to be built, and one manual lane may be eliminated.

7.3.5 2010 Build Alternative Capacity

If Tren Urbano does get built, the capacities needed at the Buchanan plaza will most likely decrease since the Tren Urbano line will serve much of the same transportation corridor as PR-22 does in the SJMR, decreasing traffic on the expressway near the plaza. (Note that this will not be true of other plazas on PR-22 which are located beyond the area which Tren Urbano will serve. However, these plazas are not nearly as congested as the Buchanan Plaza.)

The peak hour demand for the build option is 9653 vph in the dominant direction and 2151 vph in the non-dominant direction, according to the SJMR Transportation Model.[61] This is significantly lower than even 1990's demand level. However, the current capacity of the plaza is still short:

9653 vph demand - 8020 vph capacity (current) = 1633 vph short in dominant direction

Fortunately, all of this capacity is available from the non-dominant direction by reversing non-dominant lanes as in the other cases above. The excess capacity in the non-dominant direction is:

5540 vph capacity - 2151 vph demand = 3389 vph excess capacity

Thus, by reversing three of the ten non-dominant lanes, the necessary capacity for the dominant direction (9653 vph) can be achieved, as shown in Table 7.10.

Table 7.10

Capacity of Buchanan Plaza - 2010 Build - Dominant Direction (ACM and manual lanes only)

number/type of lane	capacity per lane (vph)	total capacity (vph)
3 manual lanes	400	1200
14 ACM lanes	620	8680
Total Capacity		9880

For the non-dominant direction, the capacity achieved is 3680 vph, as shown in Table 7.11. Since this is approximately 1529 vph over the 2151 vph demand, two of the ACM lanes can be eliminated.

[61] Cambridge Systematics.

From this analysis, without any ETC system, the impact of building Tren Urbano can be seen: while in the 2010 No-build Alternative, five lanes must be added to the plaza without an ETC program, for the 2010 Build Alternative, two lanes can be eliminated.

Table 7.11

Capacity of Buchanan Plaza - 2010 Build - Non-Dominant Direction (ACM and manual lanes only)

number/type of lane	capacity per lane (vph)	total capacity (vph)
3 manual lanes	400	1200
4 ACM lanes	620	2480
Total Capacity		3680

7.3.6 2010 Build Alternative ETC Design

Under the build alternative, an ETC system may still be desired, even though the increases in capacity are not needed. Benefits cited in section 7.3 such as patron convenience, public acceptance of tolling, and revenue protection are still important and may be a sufficient justification for installation of ETC.

Assuming once again that the ETC market penetration has reached 40% by 2010, the demand for ETC in the dominant direction will be:

9653 vph demand * 40% ETC penetration = 3861 vph ETC demand

This calls for the use of three dedicated ETC lanes and one mixed ETC/ACM lane. Table 7.12 shows the capacity, with four ACM lanes reversed from the non-dominant direction once again. Thus, the dominant direction demand is satisfied.

The dominant direction configuration leaves 6 lanes to be configured for the non-dominant direction. In the non-dominant direction, assuming a 40% market share:

Table 7.12

Capacity of Buchanan Plaza - 2010 Build - ETC Configuration (dominant direction, 4 reversed ACM lanes added)

number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
3 manual lanes (400 vph)	1200	***	1200
11 ACM lanes (620 vph)	6820	***	6820
1 mixed ETC lane (700 vph)	700	261 ETC 439 ACM	700
3 dedicated ACM lanes (1200 vph)	3600	3600	1200
Total available capacity			9920

*** indicates demand consistent with manual/ACM lane configuration

Table 7.13

Capacity of Buchanan Plaza - 2010 Build - ETC - Non-Dominant Direction (non-dominant, 4 reversed ACM lanes subtracted)

number/type of lane	lane capacity (vph)	demand (vph)	available capacity (vph)
3 manual lanes (400 vph)	1200	***	1200
2 ACM lanes (620 vph)	1240	***	1240
1 dedicated ACM lanes (1200 vph)	1200	860	860
Total available capacity			3300

*** indicates demand consistent with manual/ACM lane configuration

2151 vph demand * 40% ETC penetration = 860 vph

Although this level is near the threshold for a mixed ETC/ACM lane (700 vph), a dedicated ETC lane is more desirable. Table 7.13 shows the capacity in the non-dominant direction with one dedicated ETC lane.

In the non-dominant direction, there will be excess capacity:

3300 vph capacity - 2151 demand = 1149 vph over capacity in non-dominant direction

Therefore, a manual lane and an ACM lane (total capacity 1020 vph), for instance, could be permanently closed, (providing the mix of patrons using the plaza does not require all three manual lanes to be open to reach the appropriate capacity.)

In the 2010 Build Alternative situation, with a strong ETC program, two lanes of the current plaza can be closed, while increasing the level of service and providing ETC as an alternative payment method with non-stop ETC lanes. The additional benefits of ETC which are not related to capacity will also be available.

7.3.7 Conclusions from Capacity Analysis

The capacity analysis has shown that the current Buchanan plaza configuration clearly is not sufficient to handle the current traffic at the plaza. Using estimates of 1996 demand, it is possible to reverse 4 of the non-dominant direction lanes to greatly improve the service in the dominant direction with only minimal harm to the non-dominant direction. Addition of an early ETC system could increase capacity to the current demand levels.

For the 2010 No Build Alternative, where Tren Urbano is not constructed, reversing of some non-dominant direction lanes and constructing an additional five lanes will be necessary to accommodate all the demand. It is clear that the current configuration under the no build alternative will cause major delays. (The total delays will be analyzed in the next section.) If ETC is added now, with market penetration reaching 40% by 2010, the plaza will not have to be expanded in terms of physical lanes, but several ETC lanes will have to be installed.

For the Build Alternative, where Tren Urbano is built, the demands for this plaza sink below 1996 levels. For a non-ETC configuration, there will be enough capacity with the current number of lanes by reversing three of the non-dominant lanes for dominant use, and two lanes

Table 7.14

Buchanan Plaza Capacity Summary

Situation/Lane Mix	Manual	ACM	ETC/ ACM	Dedicated ETC	Demand (vph)	Available Capacity (vph)
Current Year - Current Configuration - 24 lanes						
-Dominant	3	11	0	0	11,066	8020
-Non-Dominant	3	7	0	0	3120	5540
Current Year - Alternative Configuration - 24 lanes						
-Dominant	3	15	0	0	11,066	10,500
-Non-Dominant	3	3	0	0	3120	3060
Current Year - ETC Configuration - 24 lanes						
-Dominant	3	13	0	2	11,066	11,473
-Non-Dominant	3	2	1	0	3120	3140
2010 No Build - Non-ETC Configuration - Five new lanes - 29 lanes						
-Dominant	3	19	0	0	12,696	12,980
-Non-Dominant	3	4	0	0	3386	3680
2010 No Build - ETC Configuration - Possible 1 manual lane closed - 23 lanes						
-Dominant	3	10	1	4	12,696	12,900
-Non-Dominant	3	1	1	1	3386	3720
2010 Build - Non-ETC Configuration - Possible 2 ACM lanes eliminated - 22 lanes						
-Dominant	3	14	0	0	9653	9880
-Non-Dominant	3	2	0	0	2151	2440
2010 Build - ETC Configuration - Possible 1 manual, 1 ACM lanes eliminated - 22 lanes						
-Dominant	3	11	1	3	9653	9920
-Non-Dominant	2	1	0	1	2151	2280

could be eliminated. If an ETC program with 40% market penetration is in place by 2010, again two physical lanes can be eliminated from the plaza, however additional non-capacity benefits of ETC, such as patron satisfaction and convenience would be added.

Table 7.14 provides a summary of the capacity analysis in each situation. In each case, except for the current year ETC configuration, ETC has helped increased capacity and reduced total needed lanes. More importantly, the impact of building Tren Urbano can be readily seen in the difference between 29 lanes required in the non-ETC option without Tren Urbano (no build) and 22 lanes required in the non-ETC option with Tren Urbano (build.)

As noted, even for the 2010 build option, ETC may provide a myriad of benefits, as mentioned, which do not rely on increases in capacity from ETC. Thus it is important not to evaluate ETC benefits solely on capacity analysis.

7.4 Queuing analysis

In this section, a queuing analysis for the Buchanan plaza is given using the model described in Chapter 5. Total, average, and maximum wait times, as well as maximum queues will be presented. The current year queuing will be investigated under current configuration, under the suggested alternative configuration, and finally under an ETC configuration. A 2010 no build alternative analysis, utilizing only the maximum capacity available out of the current plaza and an ETC configuration with increased capacity will follow. Finally, the 2010 build alternative with current maximum capacity and ETC capacity will be examined.

7.4.1 Current Year Queuing

Data for the demand around the Buchanan plaza for the current year is only obtainable for each of the peak hours from the SJMR Transportation Model, not for the non-peak hours. However, transaction data for peak hours is available in limited quantity. By making some assumptions, total demand by hour for the dominant direction in the morning peak can be determined.

As in the Massachusetts Turnpike queuing, it can be assumed that the capacity of the Buchanan plaza is exceeded by demand for only two hours, from 7:00 to 9:00 AM. This maximum demand is assumed to be 11,066 vph as in the capacity analysis above. Demand for the remaining hours cannot be found since transaction records in the dominant direction are not available. However, given the similarities in location, size, peak flow, and peak traffic as a proportion of all traffic, the Buchanan plaza compares roughly to plaza 19 of the Massachusetts Turnpike. Thus, it is proposed that the transactions processed at the Buchanan plaza are proportional to the data for the Massachusetts Turnpike on an hour by hour basis. Therefore a scale parameter is needed to determine the demands at the Buchanan plaza. There are several options for choosing such a parameter. Table 7.15 gives a list of parameters considered.

Table 7.15
Scale Parameter Comparison

	Buchanan	MassPike	Ratio
Maximum Transactions for 1 Hour	8000	4900	1.63
Average Trans. for 6:00-9:00 AM	20367	12338	1.65
Number of Lanes in Dominant Direction During Peak	14	10	1.4
Total Lanes in Plaza	24	15	1.6

Sources: Massachusetts Turnpike Toll Audit Department and Puerto Rico Highway and Transportation Authority.

The scale of the two plazas is around 1.6. By scaling up the MassPike data, and by adding the high estimate of demand from the transportation model (11,066 vph) for the 7:00 - 9:00 time period, the arrivals (demand) column of Table 7.16 is formed. Then, the technique in Chapter 5 can be used for a queuing analysis. Table 7.16 gives the complete results under the current capacity of the Buchanan plaza in the dominant direction.

Table 7.16

Queuing Model Spreadsheet Outputs for Buchanan Plaza of Puerto Rico Morning Dominant Direction, Current Conditions

Hour	Arrivals	Cum Arr	Departures	CS	Q Length	Cum Dep	Tot Delay
0		0	8000		0	0	0
1	422	422	8000	-7578	0	422	0
2	259	682	8000	-7741	0	682	0
3	150	832	8000	-7850	0	832	0
4	178	1010	8000	-7822	0	1010	0
5	333	1342	8000	-7667	0	1342	0
6	1595	2938	8000	-6405	0	2938	0
7	4600	7538	8000	-3400	0	7538	0
8	11066	18604	8000	3066	3066	15538	1533
9	11066	29670	8000	3066	6132	23538	6132
10	6162	35831	8000	-1838	4294	31538	11345
11	3608	39439	8000	-4392	0	39439	13444
12	3333	42772	8000	-4667	0	42772	13444
13	3275	46047	8000	-4725	0	46047	13444
14	3098	49145	8000	-4902	0	49145	13444
15	3294	52439	8000	-4706	0	52439	13444
16	3472	55911	8000	-4528	0	55911	13444
17	3902	59814	8000	-4098	0	59814	13444
18	4643	64457	8000	-3357	0	64457	13444
19	4765	69222	8000	-3235	0	69222	13444
20	2885	72106	8000	-5115	0	72106	13444
21	1790	73897	8000	-6210	0	73897	13444
22	1848	75745	8000	-6152	0	75745	13444
23	1662	77407	8000	-6338	0	77407	13444
24	946	78353	8000	-7054	0	78353	13444

Total Wait Time: 13,444 veh hrs   Average Wait Time: 10.3 min.

Maximum Wait: 46 min.   Maximum Queue: 6132 veh.

Average Wait Time For Those Who Must Wait: 25 min.

It is plain to see that the queuing situation at the Buchanan plaza has a very poor level of service. This is due mostly to the peaking load for the 7:00 - 9:00 hours. Since the San Juan Transportation Model likely gives the maximum demand, the situation where the traffic is somewhat less should be examined. Table 7.17 gives the queuing model results for peak demands, and 5% and 10% lower than the peak demands. The -5% results are assumed for an average day.

Roughly speaking, average days will produce about 20 minute waits for those who wait during the peak hour. This figure lowers to 15 minutes on slow days, and rises to 25 minutes on peak demand days. However, even on average days, 20 minutes is a very long time to wait. (Based upon conversations with users of the roadway, these wait times are not unrealistic.)

Table 7.17

Queuing Results for Buchanan Plaza at Full, 95%, and 90% Demand

	Full	-5%	-10%
Total Wait (vehicle hours)	13,444	9884	6836
Maximum Wait (min.)	46	38	29
Average Wait (min.)	10.3	8.0	5.8
Ave. Wait for Those Who Wait (min.)	25	20	15.5
Maximum Queue	6132	5025	3919

7.4.2 Current Year Queuing with 4 Lanes Reversed

As suggested in the capacity analysis section, the throughput for the dominant direction could be increased to 10,500 vph by reversing four of the non-dominant lanes, without significantly affecting the non-dominant direction level of service. Table 7.18 gives the queuing results for this situation.

Table 7.18 Queuing Results for Buchanan Plaza at Full, 95%, and 90% Demand 4 Lanes Reversed From Non-Dominant Direction			
	Full	-5%	-10%
Total Wait (vehicle hours)	1280	25	0
Maximum Wait (min.)	9.31	~0	0
Average Wait (min.)	1	~0	0
Ave. Wait for Those Who Wait (min.)	3.2	~0	0
Maximum Queue	1132	25	0

Thus, although total high demand is not served completely, it is served adequately with only a 1 minute average wait time for those who wait and 9 minute wait time for the maximum wait. On average and below average days, the waits are negligible, and the level of service is very good.

7.4.3 Current Year Queuing with ETC System

As noted in the capacity analysis, for the current year, a maximum throughput of 11,473 vph is possible with two dedicated ETC lanes, 3 manual lanes, and 13 ACM lanes in the dominant direction, morning peak. (Four lanes were reversed from the non-dominant direction without affecting non-dominant service. See Table 7.5.) Thus, there would be no queues under this plan, even on the highest demand days.

7.4.4 2010 No Build Alternative (for Tren Urbano) Queuing

For the situation where Tren Urbano is not built, the maximum demand increases to 12,696 vph for the peak hours. Also, it should be assumed that all traffic (even non-peak hours) increases 12.3% from 1990 to 2010.[62] A linear interpolation implies an increase of 8.6% from

[62] Increases in Traffic Volumes for 2010, PR22 station, *San Juan Regional Transportation Plan*, Commonwealth of Puerto Rico, March 1993, Table 4.1.

1996 to 2010. So, all traffic will be assumed to increase by 8.6% over current conditions and peak traffic will increase to 12,696 vph.

The maximum capacity achievable with the current physical lane count can be arrived at by reversing 3 non-dominant ACM lanes, as mentioned in the 2010 No Build capacity analysis. This gives a configuration of 3 manual and 14 ACM lanes with a resulting capacity of 9880 vph (without affecting non-dominant service.) Table 7.19 gives the resultant queuing figures. Without expanding the current plaza, but using the optimum arrangement of reversible lanes, for the 2010 situation without Tren Urbano, the level of service at Buchanan plaza is fairly low for peak days, with an average wait of 7 minutes and a maximum wait of a half hour.

Table 7.19

Queuing for 2010 No Build, for Buchanan Plaza at Full, 95%, and 90% Demand, 3 Lanes Reversed

	Full	-5%	-10%
Total Wait (vehicle hours)	10,171	1464	162
Maximum Wait (min.)	34	11	1.7
Average Wait (min.)	7	1	.1
Ave. Wait for Those Who Wait (min.)	18	3.3	.4
Maximum Queue	5632	1265	159

For average days (-5%), the waiting times are much lower. Table 7.19 queuing results should be compared to the optimal 1996 table (Table 7.18), where the maximum wait was only 9 minutes, with a 1 minute average. Thus, the traffic growth to the year 2010 will make a large impacts on the expected delays on peak days, even if the plaza is reconfigured to maximize throughput.

7.4.5 2010 No Build Alternative (for Tren Urbano) Queuing with ETC

As noted in the capacity analysis, a capacity of 12,900 vph can be achieved with the current number of lanes by installing 4 dedicated ETC lanes and 1 mixed ETC/ACM lane while reversing four lanes from the current non-dominant direction. With this capacity, no queues will build in the lanes. (A 40% ETC market penetration is assumed.)

7.4.6 2010 Build Alternative (for Tren Urbano) Queuing

If Tren Urbano does get built, as noted in the capacity analysis section, it is noted that the maximum demand will shrink to 9653 vph. With the optimal configuration of the current toll plaza, a capacity of 9880 vph can be reached, as noted above. Thus, no queues would build. The impact of Tren Urbano can be seen here, where even on maximum demand days, no queues are formed, and two lanes are eliminated from the plaza.

7.4.7 2010 Build Alternative (for Tren Urbano) Queuing with ETC

The capacity available for an ETC system with 40% market penetration is 9920 vph. Thus, once again, the total demand is satisfied by the system, and no queues will form.

7.4.8 Conclusions from Queuing Analysis

Table 7.20 provides a summary of the queuing analysis for different demand and lane configurations. Clearly, for the current year, some changes can be made to improve service at the plaza without an ETC system. The ETC scenario further reduces wait times for the current year.

In the case where Tren Urbano is not built, an ETC system becomes essential in order to keep the plaza from becoming excessively congested. However, if Tren Urbano is built, an ETC system will not be necessary from a queuing viewpoint in order to improve the level of service. However, an ETC system is worth considering in the situation where Tren Urbano is built in order to improve non-queuing related service characteristics at the plaza such as patron convenience, public acceptance of tolling, and revenue protection. Analysis of the benefits of ETC cannot be based only on queuing analysis results.

Table 7.20

Buchanan Plaza Queuing Summary

Situation	Max. Wait (minutes)	Ave. Wait* (minutes)
1996 Demand - Current Configuration	46	25
1996 Demand - Alternative Configuration	9.3	1
1996 Demand - ETC Configuration	0	0
2010 No Build Demand - Non-ETC Configuration	34	7
2010 No Build Demand - ETC Configuration	0	0
2010 Build Demand - Non-ETC Configuration	0	0
2010 Build Demand - ETC Configuration	0	0

*for those who do wait

7.4.9 An Important Note on Capacity and Queuing

The analyses given here, of course, assume that the downstream roadway can handle the high processing rates of future proposed configurations without backups into the plaza itself. This is somewhat unlikely, since the roadway is currently two lanes, and two lane highways generally can process no more than 4,000 vph.[63] In addition, there are several bottlenecks downstream of the Buchanan plaza that could cause traffic to back up into the plaza. Analysis of this situation is beyond the scope of this research.

[63] Maximum flow, ideal conditions, *Highway Capacity Manual*, Transportation Research Board Special Report, No. 209, 1985, pg. 3-8.

7.5 Cost analysis

This section will show the results of a cost analysis of the Buchanan plaza.[64] The current non-ETC configuration, an alternative non-ETC configuration, and an ETC configuration will be analyzed. Resulting costs, on a per-transaction basis will be presented.

Throughout this analysis, the Buchanan plaza will be presented for the inbound direction only. The rationale for analysis for one direction is in the equipment investments which must be made and the operational characteristics of the two directions of the plaza.

First, since the plaza is mostly used by those visiting San Juan for one day or commuting to San Juan for one day, over the course of one day, the flow into and out of the city, and through the Buchanan Plaza should be balanced (inbound and outbound.) Of course, flow in the morning will be mostly into the city (dominant direction in this analysis) and in the evening will be mostly out of the city (non-dominant direction in this analysis.) The costs presented are for equipment and operations. Thus, operational and equipment costs that are presented on a per-plaza basis must be halved to get the costs for the inbound direction.

Second, it may be argued that equipment costs for reversible lanes should be split down the middle also, with half the cost attributed with each direction of operation. However, each reversible lane will have to have two sets of equipment since drivers sit on the left side of the vehicle, where the manual or ACM collection equipment must be located. This is also true for ACM gate arms (two arms are needed in a reversible lane). For ETC lanes, the equipment needs to be arranged to read tolls and use violation enforcement equipment in both directions, thus requiring two sets of equipment. Therefore, reversible lane equipment is counted on a per-direction basis, not split between the two different directions. In other words, full lane equipment costs will be attributed to each lane in the dominant direction.

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[64] The fundamental techniques used for the cost analysis presented are an expansion of a technique described by R. Gobeille in "How Much Will ETTM Cost You? Maybe Not as Much as You Think", *IBTTA 62nd Annual Meeting*, November, 1994.

There are basically two components to a toll plaza cost analysis: labor and equipment. Labor is for the toll collectors and plaza supervisors. Equipment includes ACM machines and ETC components. Additional costs of an ETC program have to be added in, such as marketing and tag office operations, as noted below.

First, the costs associated with equipment should be examined. In section 3.4.2, several estimates of lane equipment costs were presented. Table 7.21 shows these costs depreciated over a 10 year life. Also included is the maintenance cost and collection costs, to give the total annual cost for each type of lane, not including labor. (Collecting and counting costs are the annual charge from a bank to collect the toll vaults from ACM machines and tolls from manual lanes then count and process the currency, crediting the toll authorities account.)

Table 7.21
Annual Lane Costs By Lane Type

Lane Type	Capital	Annual Depreciation	Collecting and Counting	Maintenance	Total
Manual	$58,500	$5,850	$4,000	$1,000	$10,850
ACM	$58,000	$5,800	$7,000	$2,000	$14,800
ETC/ACM	$69,500	$6,950	$4,000	$4,300	$15,250
Dedicated ETC	$15,400	$1,540	$0	$2,350	$3,890

Note: this table does not include labor costs or other costs which are not on a per lane basis. Sources: *Electronic Toll and Traffic Management (ETTM) Systems*, NCHRP Synthesis 194, Transportation Research Board, 1993. R.J. Gobeille, "How much will ETTM Cost you? Maybe Not as Much as You Think", IBTTA 62nd Annual Meeting, November, 1994.

Next, the costs associated with labor need to be outlined. For each lane per hour which is manual or ACM operated with a lane-walker, there is the cost of one hour's labor. For Puerto Rico, this amount is difficult to estimate because the cost of labor is lower than in the mainland United States. For most systems, the annual salary of a toll collector is estimated as $35,000 including benefits.[65] The U.S. per capita income is $20,810[66]. Puerto Rico's per capita income is $6693.[67] Thus, the wage rate for Puerto Rican toll collectors is estimated as:

[65] ibid., pg. 2.

$35,000 * $6693 / $20,180 = $11,608

Based on a 40 hour work week, 52 weeks a year, this divides down to:

$11,608 / 52 / 40 = $5.58 / hour

This wage rate will be used for the labor rate for manual lanes and ACM lanes with lane-walkers.

Also included in the labor costs is the toll plaza supervisor's salary. At an estimated $50,000[68] annual income, adjusted for the per capita income in Puerto Rico:

$50,000 * $6693 / $20,180 = $16,583

is the assumed annual salary for toll supervisors in Puerto Rico. Each plaza requires a round the clock supervisor, which requires 5 supervisors per plaza per year. This amount can be divided in half for this analysis, since the analysis is only for one direction, or one half of the traffic. Thus, the supervisory labor cost for this analysis is:

$16,583 * 5 collectors / 2 = $41,458 / year

7.5.1 Current Configuration Cost

In order to determine the total cost of the Buchanan plaza under current operations, it is necessary to determine the lane configuration throughout the day. Table 7.22, using the demand rates and lane capacities as described in the queuing analysis, shows a fairly optimal

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[66] Per capita personal income, 1993, *Statistical Abstract of the United States*, U.S. Department of Commerce, Bureau of the Census, 1995, table 706, pg. 456.
[67] *Puerto Rico's Tren Urbano - Putting Transit Innovation On-Track for the 21st Century*.
[68] Gobeille, pg. 2.

open lane arrangement, covering the demand as much as possible while reducing labor costs. (Note that this is a hypothetical lane open arrangement. For a more precise analysis,

Table 7.22

Hourly Lane Configuration for Buchanan Plaza, Current Configuration (Demand, Supply, and Labor Cost, inbound)

	Type and Number of Lanes			Flow Characteristics		Labor Cost
Hour	Manual	ACM	ACM with Lane-Walkers	Demand	Supply	Total Cost*
1	1	1	0	422	900	$5.58
2	1	1	0	259	900	$5.58
3	1	1	0	150	900	$5.58
4	1	1	0	178	900	$5.58
5	1	1	0	333	900	$5.58
6	2	2	0	1595	1800	$11.16
7	3	7	0	4600	4700	$16.74
8	3	0	11	11066	8020	$78.12
9	3	0	11	11066	8020	$78.12
10	3	0	11	6162	8020	$78.12
11	3	0	11	3608	8020	$78.12
12	2	6	0	3333	3800	$11.16
13	2	5	0	3275	3300	$11.16
14	2	5	0	3098	3300	$11.16
15	2	6	0	3294	3800	$11.16
16	2	6	0	3472	3800	$11.16
17	3	6	0	3902	4200	$16.74
18	3	7	0	4643	4700	$16.74
19	3	8	0	4765	5200	$16.74
20	3	4	0	2885	3200	$16.74
21	2	2	0	1790	1800	$11.16
22	2	3	0	1848	2300	$11.16
23	2	2	0	1662	1800	$11.16
24	2	1	0	946	1300	$11.16
Totals				78353	85580	$535

Based on $5.58 / hour per toll collector for manual and ACM lanes with lane-walkers, $0 labor for ACM lanes without lane-walkers

information on actual lane open configurations needs to be collected. However, note that the maximum number of lanes available during the peak, 14, and the maximum number of lanes open in the afternoon, 11, is current practice at the toll plaza.[69]) The lane-walker lanes are kept open at maximum capacity for 2 hours after the peak demand hours to clear the queue as fast as possible.

For this configuration, the daily labor cost for lane operations is $535. Yearly, this amounts to $195,523. Also, 78,353 transactions per day translates into 28.6 million transactions a year, which is needed for per transaction cost calculation. Table 7.23 gives the total cost and per transaction cost for the Buchanan plaza under current operations.

The cost per transaction for the current plaza arrangement is $.015. Note that this is approximately 4% of the $.35 toll for passenger cars at this plaza. This is a fairly common percentage for toll collection using manual and ACM lanes, based on other studies in the toll collection field.

Table 7.23

Cost Analysis for Current Buchanan Configuration

Item	Number Needed	Cost/Item	Total
Manual Lane	3	$10,850	$32,550
ACM Lane	11	$14,800	$162,800
Plaza Supervision	**	**	$41,458
Labor	**	**	$195,523
Total			$432,331
Transactions	78,353 Daily		28,598,845 Yearly
Cost per Transaction			$.015

7.5.2 Alternate Configuration Cost

As had been suggested in the queuing analysis, reversing four of the ACM lanes from the outbound direction for use in the inbound dominant direction during the morning peak would significantly help the throughput at this plaza. Thus, during the peak morning hours, 4 more ACM lanes and lane-walkers must be added, as shown in Table 7.24.

[69] Data from Puerto Rico Highway and Transportation Authority, June, 1996.

Notably, the number of hours that lane-walkers must be used is lower since the queue clears faster due to the higher throughput. Therefore, besides the increases in flow and decreases in

Table 7.24

Hourly Lane Configuration for Buchanan Plaza, Alternate Configuration (Demand, Supply, and Labor Cost, inbound)

	Type and Number of Lanes			Flow Characteristics		Labor Cost
Hour	Manual	ACM	ACM with Lane-Walkers	Demand	Supply	Total Cost*
1	1	1	0	422	900	$5.58
2	1	1	0	259	900	$5.58
3	1	1	0	150	900	$5.58
4	1	1	0	178	900	$5.58
5	1	1	0	333	900	$5.58
6	2	2	0	1595	1800	$11.16
7	3	7	0	4600	4700	$16.74
8	3	0	15	11066	10500	$100.44
9	3	0	15	11066	10500	$100.44
10	3	12	0	6162	7200	$16.74
11	3	5	0	3608	3700	$16.74
12	2	6	0	3333	3800	$11.16
13	2	5	0	3275	3300	$11.16
14	2	5	0	3098	3300	$11.16
15	2	6	0	3294	3800	$11.16
16	2	6	0	3472	3800	$11.16
17	3	6	0	3902	4200	$16.74
18	3	7	0	4643	4700	$16.74
19	3	8	0	4765	5200	$16.74
20	3	4	0	2885	3200	$16.74
21	2	2	0	1790	1800	$11.16
22	2	3	0	1848	2300	$11.16
23	2	2	0	1662	1800	$11.16
24	2	1	0	946	1300	$11.16
Totals				78353	85400	$457.56

Based on $5.58 / hour per toll collector for manual and ACM lanes with lane-walkers, $0 labor for ACM lanes without lane-walkers

waiting times noted in the queuing analysis, it is also cheaper to run the plaza in this configuration, from a labor standpoint, since more lane-walkers are used but for fewer hours. Note that the $457 per day for labor translates into $167,000 per year.

The complete analysis of this configuration is given in Table 7.25. Mostly due to increases in lane costs and decreases in labor, the per transaction cost increases marginally to $.016 for this alternate configuration of the current plaza.

Table 7.25

Cost Analysis for Current Buchanan Configuration

Item	Number Needed	Cost/Item	Total
Manual Lane	3	$10,850	$32,550
ACM Lane	15	$14,800	$222,000
Plaza Supervision	**	**	$41,458
Labor	**	**	$167,009
Total			$463,017
Transactions	78,353 Daily		28,598,845 Yearly
Cost per Transaction			$.016

7.5.3 ETC Configuration Cost

Under the proposed ETC configuration given in Table 7.5, two dedicated ETC lanes are added to the plaza, along with 4 reversed ACM lanes. Besides the lane and labor costs, the capital and maintenance costs of the ETC system need to be added to the cost analysis. As shown in Table 3.4, there are several ETC related costs which occur either on a system wide or plaza wide bases. Table 7.26 gives the summary of these extra costs which must be added into the ETC configuration analysis.

As mentioned, since only half of the plaza is being analyzed, per-plaza costs can be divided in half. Also, Buchanan plaza is one of six plazas on PR22, thus only 1/6 of the per-system costs fall on this particular plaza, which are then divided in half for this analysis. So, the division factor on per-system items is 12.

The lane arrangement table for the ETC option is given in Table 7.27. The labor has shrunk again due to the installation of ETC lanes. The annual cost is now $158,862.

The total cost for the ETC configuration is then given in Table 7.28. Two items in this table need explanations. First, ETC tags are assumed to be used twice a day by nearly all ETC

Table 7.26

Yearly Additional Costs for ETC System

Item	requirements	cost per unit	annual cost
Plaza Computer	per plaza =1/2	$165,000	$8250*
Host Computer	per system = 1/12	$300,000	$2500*
Enforcement System	per system = 1/12	$100,000	$833*
Initial Marketing	per system = 1/12	$100,000	$833*
Maintenance Plaza	per plaza = 1/2	$20,000	$10,000
Maintenance System	per system = 1/12	$50,000	$4167
Enforcement	per system = 1/12	$145,000	$12,083
Tag Store	per system = 1/12	$220,000	$18,333
Total			$56,999

*all capital costs depreciated over 10 years

patrons, since most patrons are commuters who travel through the plaza twice a day. Hence, a total of:

79,000 Patrons per day in one direction * 20% ETC Market Penetration = 15,800 tags

are needed. Although tags are estimated to cost $20 per tag, this is spread over two transactions per day (each tag used twice) and hence the $10 tag cost in the table. Second, a back end fee must be added to the per transaction cost. Whether patrons pay for ETC tolls by credit card, check, or cash, there will be additional costs for processing these transactions in addition to running the tag store. Here, the fee is assumed to be 2% of the $.35 toll, the typical rate for credit card transactions charged by credit card companies.

When a 20% ETC penetration system is put into place, the average cost of transactions increases 67% (from $.015 to $.025). This is one of the primary problems encountered with systems which mostly use automatic coin collection and relatively cheap labor before conversion to ETC.

Table 7.27

Hourly Lane Configuration for Buchanan Plaza, ETC Configuration (Demand, Supply, and Labor Cost, inbound)

	Type and Number of Lanes				Flow Characteristics		Labor Cost
Hour	Manual	ACM	ACM with Lane-Walkers	Dedicated ETC	Demand	Supply	Total Cost*
1	1	1	0	1	422	2100	5.58
2	1	1	0	1	259	2100	5.58
3	1	1	0	1	150	2100	5.58
4	1	1	0	1	178	2100	5.58
5	1	1	0	1	333	2100	5.58
6	2	2	0	1	1595	3000	11.16
7	3	7	0	1	4600	5900	16.74
8	3	0	13	2	11066	11660	89.28
9	3	0	13	2	11066	11660	89.28
10	3	12	0	2	6162	9600	16.74
11	3	5	0	1	3608	4900	16.74
12	2	6	0	1	3333	5000	11.16
13	2	5	0	1	3275	4500	11.16
14	2	5	0	1	3098	4500	11.16
15	2	6	0	1	3294	5000	11.16
16	2	6	0	1	3472	5000	11.16
17	3	6	0	1	3902	5400	16.74
18	3	7	0	1	4643	5900	16.74
19	3	8	0	1	4765	6400	16.74
20	3	4	0	1	2885	4400	16.74
21	2	2	0	1	1790	3000	11.16
22	2	3	0	1	1848	3500	11.16
23	2	2	0	1	1662	3000	11.16
24	2	1	0	1	946	2500	11.16
Totals					78353	115320	435.24

Based on $5.58 / hour per toll collector for manual and ACM lanes with lane-walkers, $0 labor for ACM lanes without lane-walkers

Table 7.28 Cost Analysis for Buchanan ETC Configuration			
Item	Number Needed	Cost/Item	Total
Manual Lane	3	$10,850	$32,550
ACM Lane	13	$14,800	$192,400
Dedicated ETC Lane	2	$3890	$7780
ETC System Costs	***	***	$56,999
ETC Tags	15,800*	$10	$31,600+
Plaza Supervision	***	***	$41,458
Labor	***	***	$158,862
Total			$521,649
Transactions	78,353 Daily		28,598,845 Yearly
Cost per Transaction			$.018
Back End Fee	per transaction	2% * $.35	$.007
Cost per Transaction			$.025

**79,000 Patrons per day in one direction * 20% ETC Market Penetration = 158,000 tags*
*+The cost for tags has been depreciated over five years instead of ten as the current tags on the market wear out and need overhauls in five years. Thus, 15,800 tags * $10 = $158,000 divided by 5 years = $31,600.*

7.5.4 Cost Analysis Conclusions

Table 7.29 gives a cost analysis summary for the three different types of configurations suggested here.

From the cost analysis results, it appears that all suggested improvements from the queuing stand point have caused an increase in toll collection costs. However, these costs are a minimal part of the toll paid by patrons. The range runs from 4% of the toll for the current configuration, to 7% for an ETC configuration.

Table 7.29 Buchanan Plaza Cost Analysis Summary	
Configuration	Cost per Transaction
Current Buchanan Configuration	$.015
Alternate Configuration	$.016
ETC Configuration	$.025

The cost of toll collection using the recommended ETC configuration is about 67% higher than current collection methods. This indicates that the cost benefits of ETC may not be realized in this application for the toll authority. However, the total social cost is likely to decrease since the amount of time spent waiting in toll lines is drastically reduced. As noted in the queuing analysis, a total of 13444 vehicle hours is spent in line under the current configuration. With the suggested ETC configuration, there is no time spent in queues. Thus, the decision of whether to install ETC cannot be based only on cost analysis, but must take into account other factors.

7.6 Conclusions and Recommendations for Puerto Rico

Brief summaries of the analyses for Puerto Rico are given below in turn:

Qualitatively, Puerto Rico appears to be an excellent place for installation of an ETC systems. The toll levels, the number of repeat users, and the frequency of barrier toll plazas all contribute to the likelihood of success of an ETC system, in terms of ETC market penetration and popularity of the program among patrons. ETC may help patrons by reducing the number of stops required for toll collection and reducing the need to carry a large amount of change. ETC may benefit the authority operating the expressways by increasing revenue protection, improving public image, and helping operations by increasing available capacity. Additional benefits to commercial fleets, transit vehicles, high occupancy vehicles, and publicos may be possible if an ETC system is installed. Also, ETC may increase the chances of congestion pricing being accepted in the area. Congestion pricing could reduce traffic and encourage use of transit (such as Tren Urbano) with overall societal benefits in time savings, pollution reduction, and convenience. Thus, the qualitative analysis recommends an ETC system for Puerto Rico.

However, some concerns should be raised. Since a large proportion of tolls on the Puerto Rican expressways are currently collected through automatic coin lanes, the cost of ETC collection on a per transaction basis may be somewhat greater than current collection methods. Also, releasing more traffic flow from toll plazas close to the San Juan Metropolitan Region during peak hours (by increasing plaza capacity) may cause more congestion downstream of toll plazas due to bottlenecks and insufficient capacity of mainline roadway. This may negate the benefits of increased capacity at the toll plazas and may even worsen total waiting time over the course of an entire trip to the area. Next, enforcement of toll collection at ETC lanes may be a major issue in Puerto Rico. In addition, getting certain commercial fleets, such as publicos and taxicabs to participate in ETC programs may be difficult. Finally, coordination between the Moscoso Bridge ETC system and any new system is necessary. Thus, these concerns must be addressed if an ETC system is implemented.

For the Buchanan plaza, the capacity analysis has shown that there is unused capacity available from the non-dominant direction for the dominant direction (inbound) morning rush hour. By reversing four lanes to the dominant direction, the capacity could be increased significantly (although not to current demand levels) with little or no effect on non-dominant direction traffic. However, not reversing these lanes may be due to keeping fewer lanes open to avoid congestion downstream of the plaza or may be due to the increased costs of such a configuration, which are addressed below. Addition of an ETC system to the Buchanan plaza can help to increase capacity all the way to current demand levels, given a 20% ETC market penetration rate. Again, the concerns over downstream congested need to be addressed, however.

For the Tren Urbano No Build Alternative, in 2010 three reversed and five newly constructed ACM lanes would be needed to reach the demand levels which will occur, (while also serving non-dominant demand.) However, with the addition of an ETC system and assuming a market penetration of 40%, capacity would be able to handle all of the demand. Four dedicated ETC lanes and one mixed ETC/ACM lane along with four reversed ACM lanes are needed, which will cost some money. However, the much higher construction costs of building new physical lanes is avoided.

For the Tren Urbano Build Alternative, in 2010, it will be necessary to reverse three of the non-dominant lanes to the dominant direction to reach demand. In this scenario two of the non-dominant ACM lanes can be closed, saving money while serving all of the demand. If an ETC system is put into place with market penetration reaching 40%, demand can also be fully served, with closure of two lanes, similar to the non-ETC configuration. However, the other benefits of ETC not related to capacity will be available to patrons and the toll authority which operates the expressways, if an ETC system is installed.

Thus, assuming that Tren Urbano is built, the capacity analysis recommends not installing an ETC system and using some reversed lanes to achieve capacity necessary to accommodate demand.

The queuing analysis for the Buchanan plaza shows that there are sometimes lengthy waits in the toll plaza queues, up to 46 minutes. This lengthy wait could be reduced using the alternate configuration suggested (to about 10 minutes) or by using an ETC system (which could reduce wait times to zero.) Under the 2010 No Build Alternative for Tren Urbano, waits increase significantly, up to 34 minutes, with no ETC system but using an optimum toll plaza configuration. If an ETC system is used, however, waiting times can be reduced to zero again.

For the 2010 Build Alternative for Tren Urbano, the number of lanes at the plaza could be reduced both under traditional and electronic toll collection, as mentioned above. In both cases, capacity satisfies demand and there will be no queues.

Thus the queuing analysis recommends any of the scenarios where queues are reduced to zero: current plaza with ETC, 2010 No Build Alternative with ETC, 2010 Build Alternative with or without ETC.

The cost analysis of ETC for the Buchanan plaza reveals that, due to the current high usage of automatic coin lanes, adding ETC will significantly increase the cost of collection on a per transaction basis, from $.015 to $.025. However, the higher cost is still a small portion of the toll collected (about 7%). Nevertheless, the cost analysis recommends keeping the current toll lane configuration, with per transaction costs at $.015.

Although each of the analyses can be seen to have specific recommendations, all of the information must be taken into account when considering an ETC system for Puerto Rico.

For instance, if the goal of the toll authority is to increase capacity at the Buchanan plaza for current demand, the suggested alternative configuration could be used (without ETC.) In this situation the cost of toll collection would increase from $.015 to $.016 per transaction. The maximum wait times would be reduced from 46 minutes to 9.3 minutes, and the average wait time for those who wait is reduced from 25 minutes to 3 minutes. This is a significant benefit to society, for which patrons may be willing to pay extra tolls to offset the increased cost. The total time savings for patrons would be 12,164 vehicle hours per day.[70] This is a huge amount of time savings to society. Also, pollution will be reduced by not having vehicles idle over those 12,164 vehicle hours. Thus, increasing the capacity without using ETC may be entirely justified, even if the cost per transaction is somewhat higher. (Although, the downstream traffic problems must still be taken into consideration.)

A second example would be the installation of ETC at the Buchanan plaza for current demand. Then, queues are reduced to zero. A full 13,444 vehicle hours of waiting time are saved. Although it's true that the transaction cost rises to $.025 per transaction, the waiting time decreases alone may be enough for patrons to justify paying this extra cost. However,

[70] Based on 13,444 vehicle hours total wait for Table 7.17 and 1280 vehicle hours total wait for Table 7.18.

the myriad of unmeasured benefits goes well beyond the waiting time savings: ETC will allow patrons to do away with carrying change, or having cash for tolls; revenue protection and public image benefits will accrue to the toll authority; and increased efficiency in accounting benefits will accrue to commercial fleet operators, transit operators, and perhaps publico operators. With the addition of an express HOV lane, people may be encouraged to use transit, reducing pollution in the area. Congestion pricing may also be more favorable with the use of electronic toll collection and further reductions in traffic can be achieved. (Again, the downstream traffic congestion will still need to be considered.)

Of course, if Tren Urbano is built and reaches its goals by 2010, the traffic on PR-22 and at the Buchanan plaza will decrease, and an ETC system will not be necessary to reach the demand at the plaza. However, the other benefits of the ETC system may still justify having the system in place, especially if the benefits of having an ETC system in place from the current year until 2010 are considered. Time savings, patron convenience, revenue protection, public image, commercial fleet benefits, and transit benefits accrued over the years from an ETC system may be very large compared to the cost of having such a system.

Given the indications that ETC will be useful for the Buchanan plaza, and the overall characteristics of the remainder of the tollways in Puerto Rico which favor ETC, it is likely that installation of ETC for the entire tollway system would be beneficial. This is true especially considering that there are even more benefits to installation of an ETC system which go beyond the scope of the fundamental analysis given here. For instance, vehicles with tags can be used to probe traffic movement throughout the San Juan Metropolitan region and the rest of the island, helping traffic engineers determine where congestion will occur and allowing corrective measures, such as re-routing traffic, to be taken. Also, since ETC tags could be usable on all current and future tollways on the island, the need to pay tolls by cash everywhere can be eliminated. Future tollways (such as PR-53 which is under construction) can be designed to utilize ETC from the beginning, without the cost of retro-fit. Dedicated express ETC lanes can be installed at startup, which are cheaper to build and equip than traditional toll collection lanes.

Another scenario involving the use of ETC would be to install ETC as a payment option on a dedicated ETC lane for high occupancy vehicles (HOV) immediately, and keep traditional manual and automatic coin collection for other patrons. Given the amount of time savings experienced by such vehicles (as suggested by the Lincoln Tunnel case study in Chapter 4), many people may be encouraged to carpool and use transit or publicos. These benefits would probably be greatest at the congested toll plazas and sections of expressway close to San Juan. This type of travel is then associated with shorter trip lengths. When Tren Urbano opens, people will be more comfortable with transit and HOV travel, possibly encouraging increased ridership for Tren Urbano. Alternatively, congestion pricing could be introduced for non-HOV vehicles using a full ETC system, while allowing HOV's to use ETC and a dedicated lane with low or no tolls. When Tren Urbano is introduced, not only will the familiarity with using HOV's encourage Tren Urbano use, but the cost savings (provided congestion tolls are high enough and Tren Urbano fares low enough) will also encourage Tren Urbano use. Again, these benefits would be greatest at toll plazas and on expressways closest to San Juan.

There are a great number of benefits which can be achieved by the various scenarios suggested above, with certain costs and considerations. Also, indications are that ETC systems are successful (see Chapter 4 case studies) almost everywhere they are installed, and are becoming the future of toll collection, (considering the number of toll authorities using, installing, or planning ETC systems.) The tollways in Puerto Rico are no exception. The possible benefits from ETC, as noted above, suggest that further study of ETC for Puerto Rico's expressways is justified.

The next logical question is, "Where does toll collection and ETC for Puerto Rico go now?" Although the analysis given here, along with the models and quantifiable results presented, is a starting point, it is not the final decision on whether or not ETC should be added to the expressways in Puerto Rico.

Data used for the calculations has been pieced together from various existing sources. A carefully planned data collection project could be conducted to get a better handle on the costs and benefits of installing and using ETC. Data to be collected should include:

- Actual traffic counts by lane for each toll plaza being considered for ETC, averaged over a number of days throughout the year
- A better estimation of the demand through each toll plaza utilizing a transportation model calibrated to the current year's statistics and predicting future traffic with and without Tren Urbano, or using varying degrees of traffic for various possible demands along tollways in the future
- Actual operations and capital costs for each toll plaza being considered for ETC, including labor costs and accounting costs
- Actual operational lane configurations of toll plazas to determine improvements in current operations
- Examination of traffic congestion downstream from toll plazas, with possible modeling of effects of increasing toll plaza capacity on the road network around plazas
- Better estimations of the cost of installing ETC systems - whether for whole plazas or for exclusive HOV lanes
- Examination of possible innovative concession agreements - for instance the operation of toll collection by a bank
- A patron stated preference survey to determine how many persons would be interested in using ETC, given particular fees, discounts, time savings, etc.
- A travel survey to determine how many persons would be interested in using an exclusive HOV lane equipped with ETC (either by carpooling or transit or publico) given estimated time and cost savings (i.e. toll discounts for HOV's)

This data can then be used in conjunction with the analysis techniques given above to get a better idea of the costs and benefits of installing an ETC system. Thus, a better judgment call can be made on whether or not an ETC system is a "good idea" for Puerto Rico. This kind of detailed study may be broken into sections, and performed by various parties. For instance, the operational data and patron surveys could be conducted by University of Puerto Rico (UPR) researchers and students. Cost and transit studies could be performed by the Puerto Rico Highway and Transportation Authority. Private transportation consulting firms are probably the best option for transportation models to determine current and future demand. In this manner, each section can be completed in a timely fashion. The results can then be compiled and analyzed by either UPR or a private consulting firm with expertise in the electronic toll collection system startup and integration field.

In conclusion, Electronic Toll Collection seems to hold a myriad of benefits for the Puerto Rican expressways. The analysis here has shown what some of these benefits and associated costs might be. Further study is merited to gain more accurate knowledge of influential factors (such as installation costs and patron time savings) as well as gaining knowledge of innovative applications of ETC, such as in dedicate HOV lanes.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

There are several key points to be made from the research and results presented in this paper.

First, toll collection is very important for the funding of public road infrastructure. It will become more important in the next few decades as the availability of public funds dwindles. Projects such as the Dulles Tollway and the SR91 Toll Lanes will become more prominent as many agencies continue to plan to build new toll facilities. Some facilities will be built by government entities, others by public/private partnerships and private concessionaires under build-operate-transfer type arrangements.

This building of new toll facilities brings with it the problem of toll collection. However, a primary development in tolling technology, Electronic Toll Collection (ETC) shows great promise, both in current use and future potential, as a solution to the painful tolling process. Using a vehicle mounted "tag" and a plaza mounted transceiver, tolls can be collected without the physical exchange of currency, tickets, or tokens, allowing non-stop toll collection. ETC often has many benefits, including expanded plaza capacity, reduced queues and pollution, alternative payment methods, reduced labor costs, increased revenue security, and increased customer satisfaction. It has some problems, for example, in that it can reduce costs in certain situations, but can increase costs in others. Also, it may increase capacity beyond the capabilities of the roadway to which is connected, further exacerbating downstream congestion. However, ETC has been applied to many toll facilities in the United States with success.

Electronic toll collection cannot always provide the answers, however, and not all systems are successful. The Dulles Greenway, an extension of the Dulles Tollway, recently open in northern Virginia, is a privately built roadway that is slated to start using ETC in 1996. However, traffic demands have been one third of what was expected, and the project is not doing well.[71] Installation of the ETC system is not likely to help the lack of demand on the roadway. However, in the future, demands may grow on the roadway and ETC will probably become a favorable choice since a joint account / single tag agreement has been worked out with the Dulles Tollway and there are many non-traffic related benefits of using ETC.

General literature on the subject of ETC system and toll plaza design and integration is very thin. There are only a few publications available from government sources, such as the Transportation Research Board (TRB), from professional groups, such as the International Bridge, Tunnel, and Turnpike Association (IBTTA), and from various individual writing about specific aspects of ETC systems or specific solutions applied to particular situations. Most of the analysis and design work for ETC systems is being performed by private consultants since building this type of expertise in a toll authority is not cost effective. However, efforts should be made to consolidate the current body of knowledge so that future research can continue to improve tolling systems. It is hoped that this thesis has at least provided a starting point for this process and a picture in time of how ETC is progressing.

The first five chapters of this thesis have also provided an overview and starting point for anyone who does not have any background in electronic toll collection. Although not intended to be a complete text, it should serve to educate toll authority personnel, toll concessionaires, public officials, patrons, and the public at large about the benefits, costs, and considerations of ETC systems.

The information synthesis has shown that the difficult part of implementing an ETC program is designing and integrating ETC as part of a whole system. It is especially complicated when ETC is retro-fitted to existing toll facilities. The key aspects of ETC systems and integration can be divided into six areas:

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[71] Peter Samuel, "Above Par on the Dulles Greenway," *International Journal of Advanced Transport Infrastructure*, Issue #3, November 1995, pp. 23-24.

- ETC Technology - including transmission and data communications protocols
- Systems Design - including overall architecture, reliability, traffic operations, and accounting
- Institutional and implementation issues - including agency goals, cost, and inter-agency cooperation
- Privacy and legal issues - including use of toll transaction records and violation detection / enforcement of toll collection on ETC equipped toll lanes
- Market Penetration and marketing - including proportion of ETC usage as part of the whole and effective implementation strategies
- Evaluation and Testing - including startup and long term testing

Each area must be addressed in every application of ETC in order to completely evaluate possibilities and to obtain best results. Currently, most of this design work is performed by an outside consultant working with a toll authority. This document, however, provides an overview and some of the basic analysis techniques needed to perform such design work without the use of a consultant.

To add to the basic synthesis of information, first hand information on state of the art ETC applications was gathered through the survey of five agencies currently using ETC. These case studies represent a small portion of ETC systems used in the United States. However, many important aspects of ETC systems were brought out by the case studies: First, although generally presented for use on barrier systems, ETC seeing use on closed ticket systems. Next, generally radio frequency (RF) technology is used for communications, with other older technologies now being replaced by RF. Third, patron participation rates are fairly good (around 30%) but some systems need more investment before reaching desired usage levels. Also, patrons approve of ETC systems and usage of ETC has been increasing on most systems since inception. Finally, most toll authorities feel that the benefits of having an ETC system have outweighed the cost of the system.

The type of case study analysis given in Chapter 4 can be conducted in more detail and for a wider range of systems than was within the scope of this research. More comprehensive case studies, with careful examination of motives for ETC systems and benefits from ETC systems should be performed in the future in order to further develop the field. From such case studies and in order to evaluate such studies, a standard of evaluation should be developed. This standard can also be used by toll authorities to benchmark their own performance and determine which areas need improvement and which areas are satisfactory.

As another contribution to the evaluation of ETC systems, two very important aspects of ETC, capacity (or throughput) of ETC toll lanes in terms of vehicles processed per hour and queuing of vehicles in front of toll plazas were covered as part of the analysis presented. Generalized capacity and queuing analysis can be performed with relatively little data and a few calculations as shown in Chapter 5. The formulas and tables presented should allow any toll authority who is in the early stages of learning about ETC systems and its possibilities to perform a brief analysis of their own system. In general, the analysis shows the possible increases (or decreases) in capacity and changes in patron waiting times with various ETC configurations. This kind of analysis should help an authority to make decisions about whether to proceed with hiring a private consulting company who specializes in ETC or to continue studying ETC inside the toll authority.

By using the techniques developed in Chapter 5, a capacity and queuing analysis of a real plaza on the Massachusetts Turnpike was presented. The queuing analysis of the Massachusetts Turnpike barrier plaza 19 showed that current processing causes few delays under normal conditions. Addition of an ETC system was shown to have some effect in that current demand levels can be met, reducing all queues to zero. With ETC installed, one lane could be closed by using the extra capacity ETC provides. ETC would also provide a convenient payment method for patrons. Given the future growth of traffic on the roadway, plaza 19 was shown to need expansion. Alternatively, an ETC system could be put into place in order to handle future traffic without expansion and provide a better level of service than is seen today.

As a second example of application of the methods presented in this paper, qualitative, capacity, queuing, and cost analysis was applied to tollways in Puerto Rico. The tollways in Puerto Rico were found to be a good application of ETC from a qualitative standpoint since the tollways involve several stops to pay fairly small tolls. In addition, at the major plazas, weekday traffic is mostly commuters who could justify getting an ETC tag.

There are a number of non-capacity related benefits which ETC could bring to the tollways in Puerto Rico. Revenue protection, if adequate enforcement systems are installed, can be increased utilizing ETC systems as noted in Chapter 3. Also, commercial vehicle operations could see improvements in toll accounting and decreases in time wasted in toll queues both of which represent cost savings to commercial fleets. Similar improvements are possible for transit and publico fleets using ETC. Other possible improvements can be made in public image, patron satisfaction, toll collection costs, etc. The number of benefits is clearly very large.

For the Puerto Rico study, the Buchanan plaza of PR-22 was examined. The current toll configuration was found to be insufficient to handle the demand at the plaza. By reversing lanes available from the non-critical flow direction, the capacity could be increased to better serve current demand. Also, when ETC is considered for the system, the current demand could be filled entirely, again improving level of service for patrons, and reducing wait times to zero. The number of vehicle-hours waiting in line saved by using these configurations represents a very large social benefit. Reductions in wait times also reduce the amount of pollution produced around the plaza.

For future years, the Buchanan plaza was shown to be very short on capacity. The addition of an ETC system now may keep the plaza from being short on capacity and will avoid costly construction of whole new toll lanes. If, however, Tren Urbano is built and is successful at capturing some of the market share through the Buchanan plaza, demand will subside. A new configuration will be needed to reach demand levels, but physical expansion will not be needed. The addition of an ETC system may be desirable in this situation, even though it is not needed for capacity reasons.

The queuing analysis confirmed that wait times will increase as traffic grows through the Buchanan Plaza, unless alternate configurations and/or ETC systems are used. Again, the total vehicle hours saved was very large for the suggested configuration improvements.

It is important to note, however, that all the suggested improvements to increase capacity may flood downstream bottle-necks which may worsen congestion beyond the savings achieved upstream from the plaza. In addition, the cost analysis of the Buchanan plaza showed that ETC will probably cost 67% more per transaction than the current, dominantly automatic coin collection methods. However, the increases in cost are so small (3% of the toll collected) that other improvements, such as revenue protection, may offset the increases in cost. In addition, patrons may be willing to pay this extra amount since level of service and convenience would rise.

Some innovative applications of ETC were put forth. For instance, an exclusive HOV lane with dedicated ETC could be added to the major congested plazas in Puerto Rico. The time savings from such a lane should be quite significant, if the Lincoln Tunnel case study is taken into account. Thus, people will be encouraged to use higher occupancy transportation modes such as busses, publicos, and carpools. This type of lane may have the added benefit that people will become use to using higher density modes which could help ridership levels to increase on the Tren Urbano rail transit system when it becomes operational.

A second innovative approach was to add ETC and congestion pricing to the Puerto Rican tollways at the same time, in conjunction with an exclusive HOV lane. Similar to the SR91 lanes project in California, HOVs would pay a very low or no toll and be allowed express access through the tolls via ETC. The tolls for single occupancy vehicles can be raised in a time variant fashion to promote the use of HOVs and/or shifting trips to other time periods. ETC is seen as important if congestion pricing is to be considered since the variability in tolls may annoy patrons who do not know how much money to bring on a trip and stopping to wait in line to pay tolls when paying extra for time savings is also a problem. ETC would eliminate both of these problems since tolls are deducted from a pre-paid account (i.e. no cash or tokens needed) and stopping to pay tolls is not necessary.

Another innovation which may be possible in Puerto Rico is the use of an "expert" in accounts and cash-handling for toll collection, such as a bank. Currently, the toll collection on the island is performed by a concessionaire, and the institutional structure already exists to take advantage of leasing and toll collection concession options discussed in Chapter 3.

The data used in the Puerto Rico analysis was pieced together from existing sources. However, a more in-depth study of the situation is recommended. Several types of data and surveys were suggested at the end of Chapter 7. For instance, patron stated preference surveys can be used to determine what percentage of patrons would use electronic toll collection, giving greater accuracy when analysis of needed capacity and queuing is performed. These efforts can be split among several groups such as the University of Puerto Rico, the Puerto Rico Highway and Transportation Authority, and private consulting firms.

8.2 Recommendations

Besides the specific recommendations made above for the Puerto Rico situation, there are several general recommendations and thoughts which should be included here.

Most of this research was very difficult to conduct due to the lack of literature in the field. This was one of the primary points of the first three chapters. The availability and more importantly the consolidation of literature and research in toll collection needs much improvement. As tolling becomes a more important method of financing infrastructure, tolling and electronic toll collection research will be needed.

Second, there is no standard in the field to be used for evaluation of existing ETC systems. For instance, what can be considered a "successful ETC program"? Current practice is to report ETC market penetration rates. However, as noted in Chapter 4, the success of ETC programs must be measured according to the goals of the toll authority running the system. But this alone will not be sufficient since societal benefits and patron benefits should also be included. Without such standardization, comparisons between systems cannot be made. Without the ability to compare, toll authorities will not be able to judge whether their system is performing correctly. They may miss important improvements on other systems which may be helpful to their situation, or may miss reporting their own improvements to other systems.

Third, data collection programs for pre-ETC and post-ETC analysis are virtually non-existent. Principals of traffic engineering need to be applied to toll facilities to determine what kind of data is needed, and how much is needed to make statistically valid statements about critical parameters needed in designing tolling systems. Standard numbers and parameters for toll operations should be proven and published for use by toll authorities.

Fourth, since much of the complex analysis work done in the field is performed by private consulting firms, it may be necessary for academic institutions to cooperate closely with both toll authorities and consulting firms in order to improve the knowledge base in toll collection and make information available publicly. Neither consulting firms, toll authorities, or universities are suitably equipped to perform this task individually since various pieces of expertise lie with separate entities.

Electronic toll collection will probably be around for years to come and important information about it is lacking. Simple practices as well as complex analysis in ETC deserve examination. Perhaps this paper will provide the impetus and starting point for such research.

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Appendix A: Electronic Toll Collection Survey and Responses

A.1 ETC Survey Blank

The following six pages contain the ETC survey blank.

(Note: Table A.1 has been removed.)

Electronic Toll Collection Survey

This survey is being conducted as academic research. It will not be used for any kind of commercial venture. A summary and synthesis of the results will be sent to all participants. Please answer as many questions as possible. If they are not applicable to your facility, please enter N/A in the blank. For all items, space is left for your comments. For instance, under "Deposit required for tag/transponder (if any)", if initial tags are offered free and replacement tags cost $40, enter "Initial tag free, $40 for replacement" in the space provided. If you need additional space or wish to make additional comments, please attach extra paper.

We appreciate your participation in this survey. In addition to completing the survey, we would like to have a system map of your facilities and an annual report (if publicly published). Please return completed survey (by U.S. Mail) to:

Timothy J. Boesch
c/o Tom Humphrey, Principal Research Assoc.
MIT Center for Transportation Studies
77 Massachusetts Ave., Room 1-235
Cambridge, MA 02139

If you have questions, please call:
Tim Boesch, 617-253-7942

Please return surveys by <u>May 12, 1996</u>

Facilities Operated	
Contact:	
Title:	
Authority/ Organization	
Address	
City, State, Zip	
Phone	
Fax	

General Facilities Information

Type of Facilities (list all that apply)
(e.g. bridge, causeway, commuter roadway, rural turnpike, etc.) ____________________

Length of Facilities
(in miles) ____________________

Number of Average Daily Transactions ____________________

Are these generally **Barrier** type toll facilities (toll plazas stretch all the way across the main roadway) or **Ticket** type facilities (where users get a ticket at the entrance interchange and surrender the ticket and toll at the exit interchange?)
(Please specify by facility) ____________________

How many total toll plazas are on your facilities currently? (Both ETC and non ETC) ______________________

How many ETC equipped toll plazas are there on your facilities? ______________________

What is the range of tolls currently on your facility? (eg. $.50 - $4.00 autos, $2.00 - $8.00 trucks) ______________________

Facilities Wide Toll Lane Configuration

Toll Lanes Total ________

Toll Lanes Manual ________

Toll Lanes Automatic Coin ________

Toll Lanes Man/Coin Mixed ________

Toll Lanes Man/ETC mixed ________

Toll Lanes ETC Dedicated ________

Toll Lanes ETC Express (approximately ~ 55 MPH) ________

Other types (please specify) ________

Electronic Toll Collection System

Is ETC currently in use on your facility? ______________________

If it is not, when is ETC planned to be operational? ______________________

ETC System Name (e.g. EZ Pass) ______________________

ETC Vendor / subcontractors ______________________

Type of System (radio freq., optical barcode, surface acoustical wave, etc.) ______________________

ETC Tag/Transponder Type (read only, read-write, smart card, etc.) ______________________

Date ETC opened ______________________

% ETC Transactions of Total Transactions ______________________

% of ETC Transactions auto, commercial, transit, other? ______________________

Number of Tags in Circulation ______________________

Does system also automatically classify vehicles? (i.e. through treadles, video imaging, etc.) ______________________

Enforcement System (e.g. video, trooper, gate arm, etc.) ______________________

Pre Pay or Post Pay for Tolls w/ETC Tag? ______________________

Toll Discount or Extra Fee for ETC transactions? ______________________

Deposit Required for tag/transponder (if any) __________

Minimum balance before account replenishment required __________

Types of Payment for Tag Balance
(bank draft, cash, credit card, etc.) __________

Are Anonymous Tags Available? __________

Who operates tag/transponder office and accounting center? __________

User Installation or Professional Installation Required? __________

Tag Mounting Location
(if more than one type of tag, please indicate) __________

Most Used or Congested Toll Plaza *With ETC* Information

Does your facility have more than one toll plaza?
(If no, please skip to **System Evaluation** section.) __________

Most Used Plaza Name __________

Is this plaza in a rural, suburban, or urban area? __________

For this particular plaza:

Toll Lanes Total	_____	Toll Lanes Man/ETC mixed	_____
Toll Lanes Manual	_____	Toll Lanes ETC Dedicated	_____
Toll Lanes Automatic Coin	_____	Toll Lanes ETC Express (approximately ~ 55 MPH)	_____
Toll Lanes Man/Coin Mixed	_____	Other types (please specify)	_____

Peak hour demand at this plaza (veh/hr) __________

% of transactions at this plaza that are ETC __________

System Evaluation

1.) What was the primary motivation for your authority or organization to start using Electronic Toll Collection? Have the benefits to your authority or organization exceeded the cost of the ETC system/program?

2.) Do you have any special means of speeding up toll collection such as stationing personnel at automatic coin collection lanes to take coins and preempt signals or toll gates?

3.) What was (or will be) the cost of retrofitting for ETC? (both civil construction and ETC system components, a rough estimate per lane or for the entire facility will suffice. We are looking for general cost not exact calculations.)

4.) What is the ETC equipment ownership arrangement and toll collection arrangements?
(e.g. Toll Authority leases equipment from vendor and authority collects tolls,
Toll authority owns equipment and authority collects tolls,
Toll authority leases equipment from vendor and 3rd party concessionaire collects tolls,
ETC vendor owns equipment and collects tolls,
Concessionaire collects tolls and leases ETC equipment from 3rd party vendor, etc.)

5.) Do users of ETC generally like the ETC program and do they question the privacy of it?

6.) Have you had problems with tag reading reliability? (please explain what kind)

7.) If you have non-stop ETC lanes, have you had to restrict speeds through the plazas in order to get a good transponder reading reliability and/or in order to maintain a safe operating environment at the plazas? What is the speed restriction?

8.) Have you had problems with enforcement (both before and after ETC)? Do users try to evade tolls by not putting in enough money to automatic coin collection machines? Have users tried to "piggy back" on other vehicles with ETC by riding close to the tagged vehicle so that the ETC equipment will not notice the second car? (or by following closely to the vehicle in front in auto coin lanes?)

9.) Have you had problems with channelization before the plaza(s)? Do people change lanes at the last moment - causing users of ETC Only Lanes to become trapped in the regular traffic flow? Has there been a noticeable increase in accidents (like rear end collisions) since ETC was put into service? (channelization refers to cars getting in the appropriate lanes to use ETC, or manual, or automatic coin collection)

10.) Has ETC helped reduce the average delay motorists experience (if they experience delay) waiting in the toll booth lines? (Especially at the most crowded ETC equipped plaza, if you have more than one plaza.)

11.) During the off-peak period, has your facility decided to make more or less lanes available than were kept available during the off-peak before ETC? If so, what was the reasoning behind this?

12.) Has ETC helped reduce the queues at your toll plazas and the average wait time for vehicles?
(Please estimate percentage reduction in maximum queue length and percentage reduction in average wait time)

13.) Has time based pricing or congestion pricing been considered on your facility? If so, what sort of conclusions were reached or policies employed?

14.) Is there a significant congestion point on the roadway after one of your toll plazas (such as a major freeway interchange or arterial intersection in an urban area)? If so, has this point experienced more congestion as a result of ETC (especially during peak periods) ?
(This could conceivably happen if the toll plaza previously regulated the flow due to having a fixed capacity and now has a greatly expanded flow due to the high processing speed of ETC, resulting in a displacement of congestion from just before the toll plaza to the non-toll related congestion point after the plaza.)

Please add any addition comments, questions, or ideas you may have about this research, or any comments in general about Electronic Toll Collection systems:

This is the end of the survey. Thank you very much for your time and cooperation.
Please return by May 12, 1996

A.2 Illinois State Toll Highway Authority Response

Table A.2 Illinois State Toll Highway Authority
Facilities: Tri-State, Northwest, North-South, and East-West Tollways

General Information

Type of Facilities:	Commuter Beltway	**Total Toll Plazas:**	57
Length of Facilities:	276 miles	**ETC Toll Plazas:**	15
Average Daily Trans:	1.2 Million	**Toll Rates Autos:**	$.25 - $.95
Toll Configuration:	Barrier	**Toll Rates Trucks:**	$.50 - $3.50

Facilities Wide Toll Lane Configurations

Total:	435	**Manual/ETC:**	61
Manual:	181	**Dedicated ETC:**	4
Automatic Coin:	254	**Express ETC (~55 MPH):**	Planning Stage
Manual/Coin:	0	**Auto Coin/ETC:**	106

ETC System

Date ETC Opened:	June 1993	**Pre-pay or Post-Pay:**	Pre-Pay
ETC System Name:	IPass	**Toll Discount / Fee:**	none
ETC Vendor:	Syntonic Prime A.T. Comm Sub.	**Tag Deposit Passenger:**	$38
System Technology:	Radio Frequency	**Tag Deposit Commercial:**	$52
ETC Tag Type:	Read/Write	**Minimum Balance:**	equal to next toll
% ETC Trans. of Total:	1%	**Payment Methods for Toll Balance:**	cash, check
% ETC Trans. by Class:	98% Auto	**Anonymous Tags:**	no
Tags in Circulation:	14,000	**Tag Office / Accounting:**	Authority Operates
Auto Vehicle Class:	No	**Installation:**	User
Enforcement	Video	**Tag Location:**	Dashboard, near left window post

Most Used or Congested Plaza with ETC

Plaza Name:	York Road	**Location:**	Urban
Lanes Total:	20	**Lanes Man/ETC Mix:**	10
Lanes Manual:	10	**Lanes ETC Dedicated:**	0
Lanes Auto Coin:	10	**Lanes ETC Express (~55 MPH):**	0
Lanes Man/Coin:	0	**Lanes Auto/ETC:**	10
Peak Hour Demand	7-8AM 11,400 Veh/hr	**% of Trans. at this Plaza ETC**	6%

Table A.2: Illinois State Toll Highway Authority, Continued

System Evaluation	
Motivation for authority to use ETC?	Patron Convenience
Have benefits to authority exceeded cost of ETC system/program?	Not yet
Special means of speeding collection?	Use of “lane walkers” pre-empting barriers and pushing traffic through
Cost of retro-fit for ETC (including ETC system and civil costs)	$16 Million so far $30 Million to go
ETC equipment ownership and collection arrangement	Authority owns equipment and collects tolls
Do Users Like ETC Program?	Yes
Do users question the privacy of ETC?	No
Problems with tag reading reliability	Early generation transponders had sleeper circuits to save battery. Transponder would “fall asleep” before antenna. Problem has been corrected.
Speed restrictions on ETC only lanes for safety or tag reading reliability?	No. However, IPass Only lanes signed for 15 MPH. IPass Express will be 55 MPH
Problems with enforcement? (e.g. Toll evaders sneaking through behind ETC patrons)	Yes. Yes. Yes. Electronic toll collection increases violations, if video not used as deterrent and enforcement.
Plaza channelization problems, last minute lane changes out of ETC only lanes, increases in accidents since ETC?	Plaza geometry is more of a problem than lane changing. No increase in accidents since ETC. Signing and driver education very important
Has ETC helped reduce average patron delay?	Yes, but extent of reduction will be greater as more IPass Only lanes are added
Has ETC helped reduce queues at plazas?	No - probably not noticeably. Until participation rates reach 20%, no noticeable effect (according to consultant model.)
Has efficiency of ETC allowed authority to open more lanes in off-peak?	No changes
Has congestion pricing been considered?	No
Congestion after plazas?	There are congestion points after plazas that occasionally back up into plaza. ETC has not worsened this situation. Authority has not purposefully used barrier plazas to meter down-stream traffic.

A.3 E470 Public Highway Authority (Denver) Response

Table A.3: E470 Public Highway Authority
Facilities: E470 Public Highway

General Information			
Type of Facilities:	Commuter Roadway	**Total Toll Plazas:**	5
Length of Facilities:	5.5 miles	**ETC Toll Plazas:**	5
Average Daily Trans:	8000	**Toll Rates Autos:**	$.50
Toll Configuration:	1 barrier, 4 ramp	**Toll Rates Trucks:**	$.50 - $2.50

Facilities Wide Toll Lane Configurations			
Total:	14	**Manual/ETC:**	8
Manual:	2	**Dedicated ETC:**	0
Automatic Coin:	0	**Express ETC (~55 MPH):**	4
Manual/Coin:	0	(65 MPH, Going to 70 MPH 6/1/96)	

ETC System			
Date ETC Opened:	7/1/91	**Pre-pay or Post-Pay:**	pre-pay
ETC System Name:	ExpressToll	**Toll Discount / Fee:**	none
ETC Vendor:	X-cyte	**Tag Deposit:**	$25 refundable
System Technology:	Radio Frequency	**Minimum Balance:**	$5
ETC Tag Type:	read only	**Payment Methods for Toll Balance:**	cash, check, credit card
% ETC Trans. of Total:	33%	**Anonymous Tags:**	no
% ETC Trans. by Class:	N/A	**Tag Office / Accounting:**	Plaza Only/ Authority
Tags in Circulation:	7364	**Installation:**	Professional
Auto Vehicle Class:	yes	**Tag Location:**	Windshield interior
Enforcement	video, state patrol		

Most Used or Congested Plaza with ETC - Unavailable

Table A.3: E470 Public Highway Authority Continued

	System Evaluation
Motivation for authority to use ETC?	Tollway was designed as an uncongested, high speed beltway & to provide best access to new Denver Int'l Airport
Have benefits to authority exceeded cost of ETC system/program?	Not answered since tollway was designed for ETC
Special means of speeding collection?	No
Cost of retro-fit for ETC (including ETC system and civil costs)	No retro-fit
ETC equipment ownership and collection arrangement	Authority owns; authority collects via operations contractor
Do Users Like ETC Program?	Yes
Do users question the privacy of ETC?	No
Problems with tag reading reliability	No
Speed restrictions on ETC only lanes for safety or tag reading reliability?	No speed restrictions
Problems with enforcement? (e.g. Toll evaders sneaking through behind ETC patrons)	No
Plaza channelization problems, last minute lane changes out of ETC only lanes, increases in accidents since ETC?	No channelization problems No ETC related accidents
Has ETC helped reduce average patron delay?	Not available
Has ETC helped reduce queues at plazas?	Not available, no queues
Has efficiency of ETC allowed authority to open more lanes in off-peak?	No
Has congestion pricing been considered?	No, none planned
Congestion after plazas?	No

A.4 Texas Turnpike Authority (Dallas) Response

Table A.4: Texas Turnpike Authority
Facilities: Dallas North Tollway

General Information

Type of Facilities:	commuter roadway	**Total Toll Plazas:**	3 barrier, 20 ramp
Length of Facilities:	21 miles	**ETC Toll Plazas:**	all ETC equipped
Average Daily Trans:	306,638	**Toll Rates Autos:**	$.25 - $.50
Toll Configuration:	Barrier	**Toll Rates Trucks:**	$.60 - $1.20

Facilities Wide Toll Lane Configurations

Total:	88	**Manual/ETC:**	82
Manual:	37	**Dedicated ETC:**	8
Automatic Coin:	45	**Express ETC (~55 MPH):**	
Manual/Coin:		**Auto Coin/ETC:**	

ETC System

Date ETC Opened:	7/30/89	**Pre-pay or Post-Pay:**	pre-pay
ETC System Name:	TollTag	**Toll Discount / Fee:**	none
ETC Vendor:	AMTECH	**Tag Deposit:**	$25
System Technology:	Radio Frequency	**Minimum Balance:**	$40
ETC Tag Type:	read only	**Payment Methods for Toll Balance:**	Cash, Check, Credit Card
% ETC Trans. of Total:	40%	**Anonymous Tags:**	no
% ETC Trans. by Class:	N/A	**Tag Office / Accounting:**	Authority
Tags in Circulation:	123,350	**Installation:**	N/A
Auto Vehicle Class:	no	**Tag Location:**	Windshield, top left
Enforcement	video (being installed)		

Most Used or Congested Plaza with ETC

Plaza Name:	Barrier Plaza I	**Location:**	Urban
Lanes Total:	15	**Lanes Man/ETC Mix:**	6
Lanes Manual:	6	**Lanes ETC Dedicated:**	2
Lanes Auto Coin:	7	**Lanes ETC Express (~55 MPH):**	0
Lanes Man/Coin:	6	**Comment:**	All lanes ETC
Peak Hour Demand	7 - 9 AM, 10K vph	**% of Trans. at this Plaza ETC**	42%

Table A.4: Texas Turnpike Authority, Continued

	System Evaluation
Motivation for authority to use ETC?	Reducing queuing at barrier plazas
Have benefits to authority exceeded cost of ETC system/program?	Yes
Special means of speeding collection?	No
Cost of retro-fit for ETC (including ETC system and civil costs)	Signs/Markings @ $200,000
ETC equipment ownership and collection arrangement	Authority owns equipment and collects tolls
Do Users Like ETC Program?	Users like the system
Do users question the privacy of ETC?	Not to any great extent
Problems with tag reading reliability	No major problems
Speed restrictions on ETC only lanes for safety or tag reading reliability?	For safety, speed limit through plazas is set at 10 mph
Problems with enforcement? (e.g. Toll evaders sneaking through behind ETC patrons)	Yes, users try to evade tolls by not putting in enough money, riding close to preceding ACM vehicle, riding close to preceding ETC tagged vehicles
Plaza channelization problems, last minute lane changes out of ETC only lanes, increases in accidents since ETC?	The main problem has been non-ETC users in the ETC only lane having to change at the last moment and slowing others.
Has ETC helped reduce average patron delay?	Yes. Although traffic has increased more than 79% in the 7 years we have had ETC, delays at the toll booths are no worse than before (ETC).
Has ETC helped reduce queues at plazas?	Yes
Has efficiency of ETC allowed authority to open more lanes in off-peak?	Less. Efficiency of ETC makes more lanes unnecessary
Has congestion pricing been considered?	No. Trust agreement precludes it.
Congestion after plazas?	(no response)

A.5 Port Authority of New York and New Jersey Response

Table A.5: Port Authority of New York and New Jersey
Facilities: Lincoln Tunnel

General Information

Type of Facilities:	commuter tunnel	**Total Toll Plazas:**	1
Length of Facilities:	1.5 miles	**ETC Toll Plazas:**	1
Average Daily Trans:	48K auto, 3 K truck, 5,200 busses	**Toll Rates Autos:**	$4.00 auto $3.00 motorcycle
Toll Configuration:	barrier	**Toll Rates Trucks:**	$3.00 busses $4.00 / axle trucks

Facilities Wide Toll Lane Configurations

Total:	14	**Manual/ETC:**	
Manual:	13	**Dedicated ETC:**	1
Automatic Coin:		**Express ETC (~55 MPH):**	
Manual/Coin:		**Auto Coin/ETC:**	

ETC System

Date ETC Opened:	7/89	**Pre-pay or Post-Pay:**	pre pay
ETC System Name:	EZ Pass	**Toll Discount / Fee:**	10% discount
ETC Vendor:	AMTECH	**Tag Deposit:**	free at startup, $60 later
System Technology:	Radio Frequency	**Minimum Balance:**	2 months of tolls
ETC Tag Type:	Read Only	**Payment Methods for Toll Balance:**	check
% ETC Trans. of Total:	3%	**Anonymous Tags:**	no
% ETC Trans. by Class:	30% of busses	**Tag Office / Accounting:**	Authority
Tags in Circulation:	3500	**Installation:**	user
Auto Vehicle Class:	no	**Tag Location:**	top, external, bus only
Enforcement	video and police		

Most Used or Congested Plaza with ETC - Only one Plaza on System

Special Note:

During the weekday peak period (6:30 - 10:00 AM) the Port Authority operates a 2.5 mile exclusive bus lane providing a direct route to the tunnel avoiding regular rush hour traffic an significantly reducing travel time. Those busses that use the this exclusive lane and are enrolled in the ETC program may use the dedicated ETC lane.

Table A.5: Port Authority of New York and New Jersey, Continued	
	System Evaluation
Motivation for authority to use ETC?	For express bus lane
Have benefits to authority exceeded cost of ETC system/program?	Yes
Special means of speeding collection?	No
Cost of retro-fit for ETC (including ETC system and civil costs)	$300,000 for 1 lane (in 1988)
ETC equipment ownership and collection arrangement	Toll authority owns equipment and authority collects tolls
Do Users Like ETC Program?	
Do users question the privacy of ETC?	No - since issued to busses only
Problems with tag reading reliability	Generally, the system performs satisfactorily, however some tags have deteriorated due to water getting inside the tags. They are replaced as necessary
Speed restrictions on ETC only lanes for safety or tag reading reliability?	The approach road already has a speed limit of 35 MPH, therefore there are no special speed restrictions to maintain read reliability
Problems with enforcement? (e.g. Toll evaders sneaking through behind ETC patrons)	In regular lanes, enforcement is not an issue. In the dedicated bus lane, we have experienced difficulty with identifying and billing owners of untagged buses and keeping enrolled customers' accounts current.
Plaza channelization problems, last minute lane changes out of ETC only lanes, increases in accidents since ETC?	No
Has ETC helped reduce average patron delay?	Yes, for buses and for regular customers by segregating buses from all other traffic
Has ETC helped reduce queues at plazas?	For busses, it has made a significant difference, the affects for non-bus traffic are minimal
Has efficiency of ETC allowed authority to open more lanes in off-peak?	ETC only operates for buses only, weekdays 6:30 - 10:00 AM
Has congestion pricing been considered?	Over the course of the past five years, the agency has periodically investigated congestion pricing and has not instituted such a policy
Congestion after plazas?	Yes, the tunnel is the congestion point

A.6 Massachusetts Turnpike Authority Response

Table A.6: Massachusetts Turnpike Authority
Facilities: Massachusetts Turnpike, Callahan, Sumner, and Williams Tunnels

General Information

Type of Facilities:	rural, commuter road, tunnels	**Total Toll Plazas:**	22
Length of Facilities:	135 miles	**ETC Toll Plazas:**	1
Average Daily Trans:	437,000 total	**Toll Rates Autos:**	barriers - $.25 - $1.00 tunnels - $1.00 rural - to $5.10
Toll Configuration:	tickets-rural, barrier-urban, barrier-tunnels	**Toll Rates Trucks:**	barriers - $.75 tunnels - $2.00 rural - to $32.45

Facilities Wide Toll Lane Configurations

Total:	185	**Manual/ETC:**	2
Manual:	163	**Dedicated ETC:**	2
Automatic Coin:	20	**Express ETC (~55 MPH):**	n/a
Manual/Coin:	4	**Other types:**	37 reversible

ETC System

Date ETC Opened:	12/15/95	**Pre-pay or Post-Pay:**	post pay (monthly)
ETC System Name:	MassPass	**Toll Discount / Fee:**	no, $5.00 for statement / month
ETC Vendor:	MFS Network prime Texas Inst. Sub	**Tag Deposit:**	$1,000 surety bond or cash deposit
System Technology:	Radio Frequency	**Minimum Balance:**	post pay
ETC Tag Type:	read-write	**Payment Methods for Toll Balance:**	n/a
% ETC Trans. of Total:	8.5% commercial only	**Anonymous Tags:**	no
% ETC Trans. by Class:	all commercial	**Tag Office / Accounting:**	authority
Tags in Circulation:	2,500 (after 4 months)	**Installation:**	patron
Auto Vehicle Class:	loop and treadle	**Tag Location:**	Internal - top center of windshield
Enforcement	video		External - on top of commercial license plate

Most Used or Congested Plaza with ETC: Only 1 plaza with ETC - 4 lanes

Plaza Name:	Williams Tunnel	**Location:**	urban
Lanes Total:	4	**Lanes Man/ETC Mix:**	2
Lanes Manual:		**Lanes ETC Dedicated:**	2

Table A.6: Massachusetts Turnpike Authority, Continued	
	System Evaluation
Motivation for authority to use ETC?	The primary motive was to use the state-of-the-art technology to make the Massachusetts Turnpike more efficient and to enhance customer service.
Have benefits to authority exceeded cost of ETC system/program?	It is too early to evaluate the cost of the program.
Special means of speeding collection?	Uses tandem toll booths at high volume traffic plazas. during special holidays and emergency situations, toll collectors will manually collect tolls while wearing a toll apron
Cost of retro-fit for ETC (including ETC system and civil costs)	Currently negotiating contract
ETC equipment ownership and collection arrangement	Authority owns and operates all equipment and collects all tolls
Do Users Like ETC Program?	After four months, MassPass is very popular with authorized commercial patrons
Do users question the privacy of ETC?	
Problems with tag reading reliability	Too early to determine
Speed restrictions on ETC only lanes for safety or tag reading reliability?	The Massachusetts Turnpike does not feature high speed lanes
Problems with enforcement? (e.g. Toll evaders sneaking through behind ETC patrons)	Not a problem at this time
Plaza channelization problems, last minute lane changes out of ETC only lanes, increases in accidents since ETC?	At opening of Williams tunnel, certain commercial patrons were switching lanes after initial opening. Once Massachusetts State Police enforced proper lane use, the problem was eliminated
Has ETC helped reduce average patron delay?	Too early to determine, ETC only available at Williams Tunnel (new facility)
Has ETC helped reduce queues at plazas?	Too early
Has efficiency of ETC allowed authority to open more lanes in off-peak?	Four lanes at Williams Tunnel only
Has congestion pricing been considered?	The tunnels offer commuter resident discount tickets and carpool passes, the turnpike offers carpool passes
Congestion after plazas?	No

Appendix B: Development of Calculations for Queuing Model

As noted in Chapter 5, the development of a simple queuing model is straight forward utilizing any spreadsheet program.

Table B.1

14 Lane Plaza Queuing Example Spreadsheet Results

A Hour	B Arrivals	C Cum Arr	D Departures	E CS	F Q Length	G Cum Dep	H Tot Delay
0		0	1000		0	0	0
1	600	600	1000	-400	0	600	0
2	700	1300	1000	-300	0	1300	0
3	1300	2600	1000	300	300	2300	150
4	2000	4600	1000	1000	1300	3300	950
5	2200	6800	1000	1200	2500	4300	2850
6	900	7700	1000	-100	2400	5300	5300
7	400	8100	1000	-600	1800	6300	7400
8	400	8500	1000	-600	1200	7300	8900
9	400	8900	1000	-600	600	8300	9800
10	300	9200	1000	-700	0	9200	10057
11	400	9600	1000	-600	0	9600	10057
12	500	10100	1000	-500	0	10100	10057
13	900	11000	1000	-100	0	11000	10057
14	1100	12100	1000	100	100	12000	10107
15	1300	13400	1000	300	400	13000	10357
16	1000	14400	1000	0	400	14000	10757
17	600	15000	1000	-400	0	15000	10957
18	200	15200	1000	-800	0	15200	10957

Hourly Model

Table B.1 shows the output for the model for the theoretical toll plaza discussed in Chapter 5. The formulas for each column will be developed here.

Notation:

The letters in each column are used as a reference for constructing the equations behind the table. Also, the notation "PR" means previous row, and "CR" means current row. For example, in the equations for each column given below, (A,PR) means the value in column A, row previous to the current row being computed.

Column Explanations:

The A column, "Hour", shows the ending hour of the day for which the analysis is being done. For instance, 0 indicates the initial state of the system. The number 2 in the A column indicates the state of the system after the 2nd hour. Hence, this is just the reference number for the time of day.

The B column, "Arrivals", lists the cumulative arrivals expected at the plaza for the time period indicated. For instance, in the 4:00 -5:00 period (row 5), 2200 vehicles have arrived, on average. This is assumed to be a constant arrival rate throughout the hour.

The C column, "Cum Arr", is the cumulative arrivals at the toll plaza. This is easily calculated by setting the 0 row to 0 (no arrivals), then adding the previous hour's entry to the current hour's arrivals to reach total arrivals at the end of each hour. For instance, column C for the end of the 5th hour shows 4600 cumulative arrivals for the previous hour plus 2200 arrivals in the current hour for a total of 6800 arrivals. Hence, this calculation is:

(C,CR)=(C,PR)+(B,CR)

The D column, "Departures", is the capacity of the toll plaza (see Ch. 5 for capacity analysis), assumed to be constant throughout the day in this example. The "0" row has 1000 entered and then copied for the remainder of the column so that only one cell needs to be changed to change the entire column, assuming a constant capacity all day long. However, if capacity will be less due to certain lanes being closed at certain times, these numbers could be entered separately for each hour.

The E column, "CS", is the capacity shortfall. It is the number of arrivals in the hour (column B) minus the number of departures (column D). For instance, there are 400 arrivals in the 11th hour (10:00 - 11:00) with 1000 departures, giving a CS of -600, or 600 vehicles extra capacity for that hour, which may go unused or may be used to dissipate queues remaining from the previous hour. This calculation is then:

(E,CR) = (B,CR)-(D,CR)

The F column, "Q length", calculates the cumulative queue length (number of patrons waiting to be serviced.) This is calculated using a logical IF decision rule. If the previous hour's queue plus the capacity short fall, CS, is greater than zero, (i.e. there is still a queue remaining at the end of the current hour), then the remaining queue will be equal to the previous hour's queue plus the capacity shortfall. However, if the sum is equal to or less than zero, then there is no queue left, any remaining queue from the last hour has been dissipated, and zero is entered in the column. In this way, the queue length can be computed throughout the time period under study. The calculation for this would be:

```
1: IF [(F,PR)+(E,CR) > 0]
2:      THEN (F,CR) = (F,PR)+(E,CR)
3:      ELSE  (F,CR) = 0
```

The G column, "Cum Dep", is the cumulative departures throughout the day. This calculation is confusing because it involves a multiple level logical structure. Basically, this column provides the data for the departure line for the queue graph.

The G column can be calculated in this way:

1) If there was no queue at the end of the current hour and at the end of the previous hour, then the departure rate exceeds the arrival rate and the departures during the hour equal the arrivals during the hour. The current cumulative departures can be calculated by adding the previous hour's cumulative departures with the current hour's arrivals.

2) If there is a queue at the end of the current hour and at the end of the previous hour, then the arrival rate exceeds the capacity and the cumulative departures increases only by the capacity of the toll plaza over the course of the hour. The figure can be calculated by adding the previous hour's cumulative departures with the current hour's departure rate.

   Situations 1) and 2) cover all possibilities except when a queue begins or ends. The queue begins when the arrival rate starts to exceed the departure rate, which for this model, always occurs at the beginning of an hour. Therefore, if a queue started at the beginning of the current hour, (as indicated by a queue existing at the end of the current hour, but not at the end of the previous hour), the cumulative departures would increase by the capacity of the plaza over the hour. Therefore, the beginning of a queue is identical to situation 2), and the cumulative departures is the sum of the previous hour's cumulative departures and the departures during the current hour.

3) If the queue has ended during the hour, there is a problem. (This is possible since the remaining queue for any hour will not always be an integer multiple of the capacity.) For the first part of the hour, when there is a queue, the cumulative departures increase at the rate of capacity (or departures.) For the second part of the hour, there is no queue, and the cumulative departures increases at the arrival rate since these arrivals do not have to wait in queue. The breakpoint where the queue dissipates, of course, cannot be shown in

the table or on the graph since a time point in the middle of the hour is needed. Hence, the cumulative departures is moved to the cumulative arrivals at the end of an hour where the queue dissipates, indicating that the queue has dissipated. (This approximation will effect the calculation of total delay, as explained below.)

The total logic structure for this operation is:

```
1: IF (F,CR)=0 AND (F,PR) = 0              SITUATION 1)
2: THEN (G,CR)=(G, PR)+(B, CR)
3: ELSE IF (F, CR) = 0                     SITUATION 3)
4: THEN (G,CR)=(C, CR)
5: ELSE (G,CR)=(G, PR)+(D, CR)             SITUATION 2)
```

Lines 1 and 2 handle the situation described in 1) - no queue existed before or after the hour, i.e. (F,CR) = 0 and (F,PR) = 0. Lines 3 and 4 handle situation 3) - there was no queue at the end of the hour (F,CR)=0, but that there was a queue at the beginning of the hour (otherwise, the logic would have taken line 2 and ended.) Line 5 handles the situation where there is a queue before and after the hour (i.e. a queue exists at the end of the hour, (F,CR)!=0 and at the beginning, (F,PR)!=0, where != reads "does not equal".) As mentioned above, the situation where there is a queue at the end of the hour but not the beginning is handled by situation 2).

The H column, "Tot Delay", calculates the total amount of time spent in the queue by the patrons. It is the area between the cumulative arrivals and departures curves. Note that the time spent paying tolls is not included here since the purpose of the model is to calculate the queuing delay, not the total time spent in the toll transaction. To calculate total delay, it is necessary to examine Figure B.1. Here, set out on the x/y plane of the graph is the section for which the area is to be computed.

In Figure B.1, the upper line between (X1,Y3) and (X2,Y4) is the cumulative arrivals line over the course of one hour. The lower line between (X1,Y1) and (X2,Y2) is the cumulative departures line over the course of one hour. The figure shows that the total area between the two curves for this time period is:

$$\tfrac{1}{2}(X2-X1)(Y4-Y3)+(X2-X1)(Y3-Y2)+\tfrac{1}{2}(X2-X1)(Y2-Y1)$$

Which reduces to:

$$\tfrac{1}{2}(X2-X1)(Y4+Y3-Y2-Y1)$$

Here, X2 is the time at the end of the period, X1 is the time at the beginning of the period. Y1 is the cumulative departures at the beginning of the period, Y2 is the cumulative departures at the end of the period, Y3 is the cumulative arrivals at the beginning of the period, and Y4 is the cumulative arrivals at the end of the period. Hence, by computing this area for each time period and adding to the previous period's cumulative delay, total delay can be computed.

The calculation for this row is then:

(H,CR)=.5*[(A,CR)-(A,PR)]*[(C,CR)+(C,PR)-(G,CR)-(G,PR)]+(H,PR)

When a queue ends, the situation in Figure B.2 appears. The formula given above would calculate area A plus area B, when only area A is desired. In order to calculate this area, a logical structure will have to be added, when the queue dissipates. This structure must then calculate (X3,Y5) and then simply use the same area formula given above, but with (X3,Y5) in place of both (X2,Y4) and (X2,Y2). The area formula then reduces to:

$\frac{1}{2}(X3-X1)(Y5+Y3-Y5-Y1) = \frac{1}{2}(X3-X1)(Y3-Y1)$

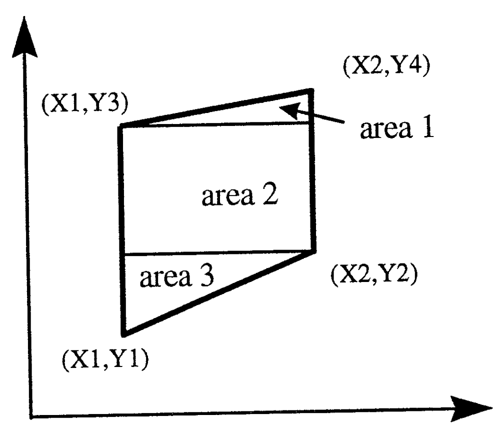
Thus the need to calculate Y5 independently is eliminated.

The time when the queue dissipates (X3), it is the fraction of the hour given by the ratio of the number of patrons left in the queue at the end of the previous time period to the excess capacity (CS). Then, this fraction of the time period, multiplied by the length of the time period (X2-X1), plus the beginning of the time period (X1) will give the time when the queue actually ends (X3). However, since the area formula calls for then subtracting X1 from X3, the difference (X3-X1) can be calculated directly as the fractional dissipation rate multiplied by the length of the time interval. So, the modified formula for total delay is:

1: IF (F,PR)>0 AND (F,CR)=0 THEN
2: THEN (H,CR)=.5*[(C,PR)-(G,PR)]*[-(F,PR)/(E,CR)]*[(A,CR)-(A,PR)]+(H,PR)
3: ELSE (H,CR)= .5*[(A,CR)-(A,PR)]*[(C,CR)+(C,PR)-(G,CR)-(G,PR)]+(H,PR)

Note that a negative sign is included in row 2 for calculating the fraction of the time period the queue remains. This is necessary since the capacity shortage (E,CR) always appears negative for an hour in which a queue dissipates.

Figure B.1
Delay Calculations for ETC Model

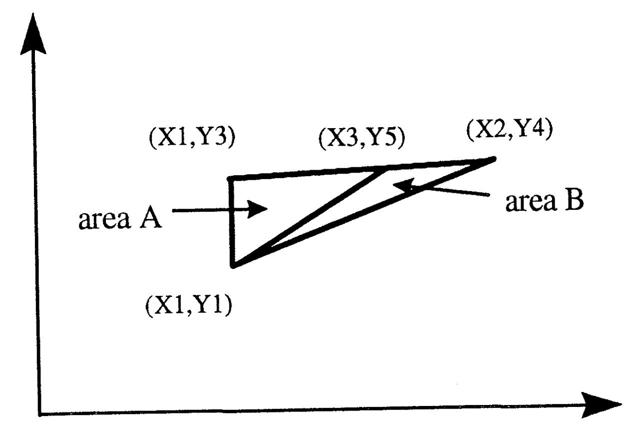


area 1 = 1/2 (X2-X1) (Y4-Y3)

area 2 = (X2-X1) (Y3-Y2)

area 3 = 1/2 (X2-X1) (Y2-Y1)

Figure B.2
Delay Calculations for ETC Model End of Queue Approximation



area A = ½(X3-X1)(Y5+Y3-Y5-Y1)

= ½(X3-X1)(Y3-Y1)

Independent Time Period Model

The model developed above uses hourly increments for computations and measurements. Hourly increments are the typical information available to planners for toll authorities from

Table B.2

Queuing Model Spreadsheet Outputs, 15 minute increments

A Hour	B Arrivals	C Cum Arr	D Departures	E CS	F Q Length	G Cum Dep	H Tot Delay
0.00		0	250		0	0	0
0.25	150	150	250	-100	0	150	0
0.50	150	300	250	-100	0	300	0
0.75	150	450	250	-100	0	450	0
1.00	150	610	250	-90	0	610	0
1.25	175	785	250	-75	0	785	0
1.50	175	960	250	-75	0	960	0
1.75	175	1135	250	-75	0	1135	0
2.00	175	1360	250	-25	0	1360	0
2.25	325	1685	250	75	75	1610	9
2.50	325	2010	250	75	150	1860	38
2.75	325	2335	250	75	225	2110	84
3.00	325	2660	250	75	300	2360	150
3.25	500	3160	250	250	550	2610	256
3.50	500	3660	250	250	800	2860	425
3.75	500	4160	250	250	1050	3110	656
4.00	500	4660	250	250	1300	3360	950
4.25	550	5210	250	300	1600	3610	1313
4.50	550	5760	250	300	1900	3860	1750
4.75	550	6310	250	300	2200	4110	2263
5.00	550	6760	250	200	2400	4360	2838

there own audits and MPO models. However, it is very simple to extend the model to any time increment. For instance, to extend the model to 15 minute increments, it is necessary to set up the table as shown in table B.2.

Here the formulas are the same as the hourly model. The only difference is that the Hour column is expressed in terms of fractions of the hour, in this case .25 hour, or 15 minute intervals. Note that the arrival rates for each time period must be expressed as arrivals/15 minute period, not per hour. In the same respect, the departures must be expressed in departures/15 minute period. In this case, 1000 vph capacity implies 250 vehicles departures per 15 minute period.

Without any other changes, the formulas will give accurate queue lengths, total wait time, average wait time (as described above), and maximum wait time, for the independent time period model.

There is an advantage to using smaller time increments even if only the average arrivals per hour are known. Note that the calculation of arrivals and departures is actually a numerical integration and using smaller increments give more accurate results.

MicroSoft® Excel Formulas

For this research, the spreadsheet calculations were programmed on MicroSoft Excel version 7.0. Table B.3 contains the first 7 hours of formulas. The natural extension of these tables for a full 24 hour spreadsheet is straight forward and not included here.

Table B.3

Spreadsheet Formulas for Queuing Model (MS Excel 7.0)

	A	B	C	D	E	F
1	Hour	Arrivals	Cum Arr	Departures	CS	Q Length
2	0		0	1000		0
3	1	600	=C2+B3	=D2	=B3-D3	=IF(F2+E3>0,F2+E3,0)
4	2	700	=C3+B4	=D3	=B4-D4	=IF(F3+E4>0,F3+E4,0)
5	3	1300	=C4+B5	=D4	=B5-D5	=IF(F4+E5>0,F4+E5,0)
6	4	2000	=C5+B6	=D5	=B6-D6	=IF(F5+E6>0,F5+E6,0)
7	5	2200	=C6+B7	=D6	=B7-D7	=IF(F6+E7>0,F6+E7,0)
8	6	900	=C7+B8	=D7	=B8-D8	=IF(F7+E8>0,F7+E8,0)
9	7	400	=C8+B9	=D8	=B9-D9	=IF(F8+E9>0,F8+E9,0)

Table B.3 Continued

Spreadsheet Formulas for Queuing Model (MS Excel 7.0)

	G	H
1	Cum Dep	Tot Delay
2	0	0
3	=IF(AND(F3=0,F2=0),G2+B3,IF(F3=0,C3,G2+D3))	=IF(AND(F2>0,F3=0),0.5*(C2-G2)*(-F2/E3)*(A3-A2)+H2,0.5*(A3-A2)*(C3+C2-G3-G2)+H2)
4	=IF(AND(F4=0,F3=0),G3+B4,IF(F4=0,C4,G3+D4))	=IF(AND(F3>0,F4=0),0.5*(C3-G3)*(-F3/E4)*(A4-A3)+H3,0.5*(A4-A3)*(C4+C3-G4-G3)+H3)
5	=IF(AND(F5=0,F4=0),G4+B5,IF(F5=0,C5,G4+D5))	=IF(AND(F4>0,F5=0),0.5*(C4-G4)*(-F4/E5)*(A5-A4)+H4,0.5*(A5-A4)*(C5+C4-G5-G4)+H4)
6	=IF(AND(F6=0,F5=0),G5+B6,IF(F6=0,C6,G5+D6))	=IF(AND(F5>0,F6=0),0.5*(C5-G5)*(-F5/E6)*(A6-A5)+H5,0.5*(A6-A5)*(C6+C5-G6-G5)+H5)
7	=IF(AND(F7=0,F6=0),G6+B7,IF(F7=0,C7,G6+D7))	=IF(AND(F6>0,F7=0),0.5*(C6-G6)*(-F6/E7)*(A7-A6)+H6,0.5*(A7-A6)*(C7+C6-G7-G6)+H6)
8	=IF(AND(F8=0,F7=0),G7+B8,IF(F8=0,C8,G7+D8))	=IF(AND(F7>0,F8=0),0.5*(C7-G7)*(-F7/E8)*(A8-A7)+H7,0.5*(A8-A7)*(C8+C7-G8-G7)+H7)
9	=IF(AND(F9=0,F8=0),G8+B9,IF(F9=0,C9,G8+D9))	=IF(AND(F8>0,F9=0),0.5*(C8-G8)*(-F8/E9)*(A9-A8)+H8,0.5*(A9-A8)*(C9+C8-G9-G8)+H8)