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A Model for the Benefits of Electronic Toll Collection System

by

Rajesh H. Chaudhary

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Industrial Engineering
Department of Industrial & Management Systems Engineering
College of Engineering
University of South Florida

Major Professor: Grisselle Centeno, Ph.D.
Tapas Das, Ph.D.
Jian John Lu, Ph.D., P.E.

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A MODEL FOR THE BENEFITS OF ELECTRONIC TOLL COLLECTION SYSTEM

Rajesh H. Chaudhary

ABSTRACT

Due to the degree of complexity related to measuring the advantage of establishing Electronic Toll Collection (ETC) systems, literature generally stops short of modeling an all-inclusive set of benefits of the system. In this research, a model that incorporates the impact on both the users and the society as a whole and evaluates the financial benefits over the lifespan of the ETC investment is developed.

Most of the values for the parameters used for calculating the benefits are taken from Federal Highway Administration (FHWA) and from similar studies conducted by transportation agencies, which is the setting that has motivated the current research. These parameters are national averages and not region specific.

The model will serve as a decision making tool to determine the number of ETC lanes over the manual and automatic lanes. The model has been used for toll plazas with different number of lanes to study the financial value of the benefits due to the ETC deployment. It is also used to study the effect of the traffic flow on the total benefits and recommendation has been made with respect to the time for the ETC deployment.

CHAPTER 1

INTRODUCTION

Transportation is the backbone of any country's economy. Advancement in transportation systems has lead to a lifestyle characterized by extraordinary freedom of movement, immense trade in manufactured goods and services, high employment levels and social mobility. In fact, the economic wealth of a nation has been closely tied to efficient methods of transportation.

Due to increasing number of vehicles on the road, problems such as congestion, incident, air pollution and many others have become a major factor of concern. Evidently, nearly all-economic activities at some point use different means of transportation to operate. For that reason, enhancing transportation will have an immediate impact on productivity and the economy.

Reducing the costs of transporting natural resources to production sites and moving finished goods to markets is one of the key factors in economic competition. This task requires that the linkage between any two states or any two places is such as to reduce travel time, reduce congestion, increase efficiency, and increase safety.

By increasing system efficiency and using modern technology the capacity of the current limited resources can be optimized. Electronic Toll Collection (ETC) systems aimed at increasing traffic flow by reducing toll transaction time. This research develops a model to study the benefits of ETC.

ETC benefits can be broadly divided into three categories: toll agency benefits, user benefits, and social benefits. The toll agency benefits include reduction in operating cost, reduction in man labor, reduction in maintenance cost, and enhanced cash handling. The user benefits include time saving due to the elimination of the hassle of digging for change and the elimination of acceleration and deceleration as the vehicles do not stop for toll transaction. In addition, there is time saving due to the reduced toll transaction time and average waiting time. Moreover, considerable fuel is save due to elimination of acceleration. The social benefits include the reduction in mobile emissions that impact the nearby areas where ETC is deployed. This research considers the user and the social benefits as they represent the biggest advantages for ETC implementation.

Although many researchers have analyzed the benefits of ETC, they have failed to present an integrated system that includes all the quantifiable factors and components. In addition, most researches estimate benefits for a particular toll plaza or facility after ETC has been implemented. It makes the benefit evaluation myopic on its nature. In this research, the benefits are estimated before the actual ETC implementation. They are calculated at an integrated basis at the design level for the toll plazas. In addition, most of the values for parameters are taken from Federal Highway Administration (FHWA) and the remaining parameters are based on the previous studies. Thus the parameters considered are national averages and not region specific which make the model more robust to provide a fair estimate irrespective of the place to which the model is applied.

The model will serve as a decision making tool to determine the effect of ETC lanes over the manual and automatic lanes. The number of these lanes will be varied to study their effect on the total benefits. The model will be evaluated using C programming and a sensitivity study will be done on the values of the parameters to verify their effect on the output of the model.

Results from the model will help the toll agencies to make decisions for ETC deployment over the manual toll to check its time and financial feasibility before the implementation of ETC. It will help to estimate the financial value of the benefits that will be produced from the ETC project. Furthermore, this research will impact the toll agencies on deciding upon the strategies related to congestion reduction and rerouting of vehicles.

The organization of this research is as follows: Chapter two provides an introduction to Intelligent Transportation Systems (ETC particularly). Chapter three summarizes the literature in ETC and related areas of its benefits. Chapter four describes the problem in detail stating the assumptions and objectives. In Chapter five, the model and its components are discussed in detail. Chapter six deals with the results and analysis of the model followed by conclusion in the chapter seven.

CHAPTER 2

INTRODUCTION TO INTELLIGENT TRANSPORTATION SYSTEMS

In order to effectively utilize transportation resources, the Intermodal Surface Transportation Efficiency Act (ISTEA) was passed in 1991. The purpose of the Act was to develop a National Intermodal Transportation System that would be economically efficient and environmentally sound. The act would also provide the foundation for the nation to compete in the global economy and would move people and goods efficiently. As a result, there was a new era for transportation, calling for more efficient and safe use of existing highways and transit infrastructure. It would also emphasize intermodalism that would be the seamless integration of multiple transportation modes. Under ISTEA, the Intelligent Vehicle-Highway Systems was established later renamed as the Intelligent Transportation Systems Program (ITS). This program emphasized the widespread implementation of intelligent [transportation] systems to enhance the capacity, efficiency, and safety of the Federal-aid highway system. It also emphasized to serve as an alternative to additional physical capacity of the Federal-aid highway system.

During the last 14 years there has been a tremendous improvement in transportation by deploying ITS technologies. The technologies used are diverse and versatile. The aim of combining telecommunication, computer, and sensing technologies is to provide real-time information to both traffic managers and travelers. The information provided would be on parameters such as on traffic and traffic congestion, weather conditions and navigation alternatives. In the future it is expected that ITS will provide the crash warnings and collision avoidance methods to increase safety. The objective is to make the system free of human errors and hence increase safety and reliability. ITS is divided into seven components depending upon the service it would provide to the transportation users. These components are discussed in the next section.

2.1 Components of ITS

ITS is aimed at providing improved services to the transportation users and depending upon the service provided it is divided into the following seven components discussed as following.

1. Advanced traveler information systems -- This component deals with the acquisition, analysis, communication, presentation and use of the information. The objective is to assist the surface transportation traveler in moving from origin to destination in the way that best satisfies the traveler needs, safety, comfort and efficiency. The travel route may depend on the choice of the traveler.

2. Advanced traffic management systems -- This component includes the technologies to monitor, control and speed the traffic flow. In case of incident, the traffic flow may be directed to decrease the congestion and speed up the traffic flow. Help to guide the paramedics to arrive earlier at the incident and thus reduce the losses.

3. Commercial vehicles operation -- This component utilizes technologies to speed the flow of the commercial vehicles and increase its safety. The technology minimizes the commercial vehicles stoppage at the weigh stations, port of entry and thus speeding the flow. This also saves a lot of time and fuel and also reduces fuel emissions.

4. Advanced rural transportation systems -- This component is aimed at enhancing the rural transportation system. Rural roads have unique set of characteristics and it comprises of the 80% of the total road mileage and 40% of the vehicles mileage.

5. Advanced public transit systems -- This component includes technologies from providing dispatchers a means of visual tracking buses to giving passengers an audio and visual display of the next bus stop.

6. Weather applications -- This component provides the surface transportation user the road conditions impacted by the weather conditions. The traveler learns about the existing conditions and warns him to take the safety measures. So this is the dynamic information system to keep the patrons informed about the latest road conditions.

7. Intelligent vehicles initiatives -- This component's long-term goal is to provide an atmosphere that is free from human errors. The technologies help to give the information to the driver and warn him against any hazards that are likely to occur due to human error. The idea is to develop vehicles that is automatic and requires lesser human input while operating.

These components help to understand the implementation areas of ITS and its classification though this classification may differ depending upon the grouping of some user functions. The user functions are explained later in this chapter. For a better understanding of ITS, the National ITS Architecture was developed with the help of USDOT and ITS America. The National ITS Architecture is discussed in the next section.

2.2 National ITS Architecture

The national ITS architecture provides a common framework for planning, defining and integrating intelligent transportation systems. It is a mature product that reflects the contributions of the broad cross section of the ITS community that includes the transportation practitioners, systems developer, systems engineer, technology specialist, consultants, etc over a period of more than five years. The National ITS Architecture contains material that will assist agencies at each step of project development. It would also help in defining about how an individual project, such as a traffic signal control project, fits into a larger regional transportation management context. So it becomes very necessary from the development point of view. The architecture defines:

1. The functions (e.g., gather traffic information or request a route) that are required for ITS.
2. The physical entities or subsystems where these functions reside (e.g., the roadside or the vehicles)
3. The information flow that connect these functions and physical subsystems together into an integrated system

There is an extensive geographic and functional scope of the National ITS and due to the requirements that drove its development, it is structured somewhat differently and uses different terminology than is typically used today in the transportation community. It was developed to support ITS implementations over a 20-year time period in urban, interurban, and rural environments across the country. Accordingly, general names were given to the physical transportation system components and locations in order to accommodate a variety of local design choices and changes in technology or institutional arrangements over time. This allows the general structure of the National ITS Architecture to remain stable while still allowing flexibility and tailoring at the local implementation level.

2.2.1 *Components of ITS Architecture*

The ITS Architecture, as suggested by ITS America, consists of User Services and User Service Requirements, Logical Architecture and Physical Architecture. There are other classifications that help us to understand the architecture such as Equipment Packages and Market Packages. These may not necessarily be a part of the architecture but they are very useful in understanding the deployment of ITS throughout the country. A brief explanation is provided for each of these terms in the remaining part of the section.

2.2.1.1 User Services and User Service Requirements

The user services are designed by keeping the user of the technology in mind. It is an important aspect to recognize, understand and enhance the services that can be provided to the user. Now these services are expected to increase the safety, decrease the congestion, reduce traveling time and aid in dissemination of the traffic information among the users for making decisions regarding the traveling patterns. A collaborative process involving USDOT and ITS America with significant stakeholder input jointly defined these user services. The important point is that the concept of user services allows the process of system or project definition to begin by thinking about what high level services will be provided to address identified problems and needs. New or updated user services may be added to the National ITS Architecture over time. Some of the user services could be Pre-Trip Travel Information, Route Guidance, Traffic Control, Electronic Payment Services, etc.

A number of functions are required to accomplish each user service. To reflect this, each of the user services was broken down into successively more detailed functional statements, called user service requirements, which formed the fundamental requirements for the National ITS Architecture development effort. For example, the traffic control user service is actually defined by over 40 functions such as traffic information, traffic control and traffic flow optimization. Many of these user service requirements can be implemented today although some of them may be more representative of future capabilities and should be deferred for now. These requirements can be used as a point from where the development of project functional requirements and system specifications can start.

2.2.1.2 Logical Architecture

It is the flow of data and information through the system at various levels. It guides the development of functional requirements for new systems by identifying the functions and information flows. The logical architecture of the National ITS Architecture defined a set of functions (or processes) and information flows (or data flows) that respond to the user service requirements. They are represented graphically by data flow diagrams or bubble charts which decompose into several levels of detail. Figure 1 shows an example for the manage traffic process interacting with seven other processes. The processes are shown in form of rectangular boxes and arrows show their interactions. Here the process of traffic management receives and gives information to other seven processes. For instance, traffic data can be used to manage transit services.

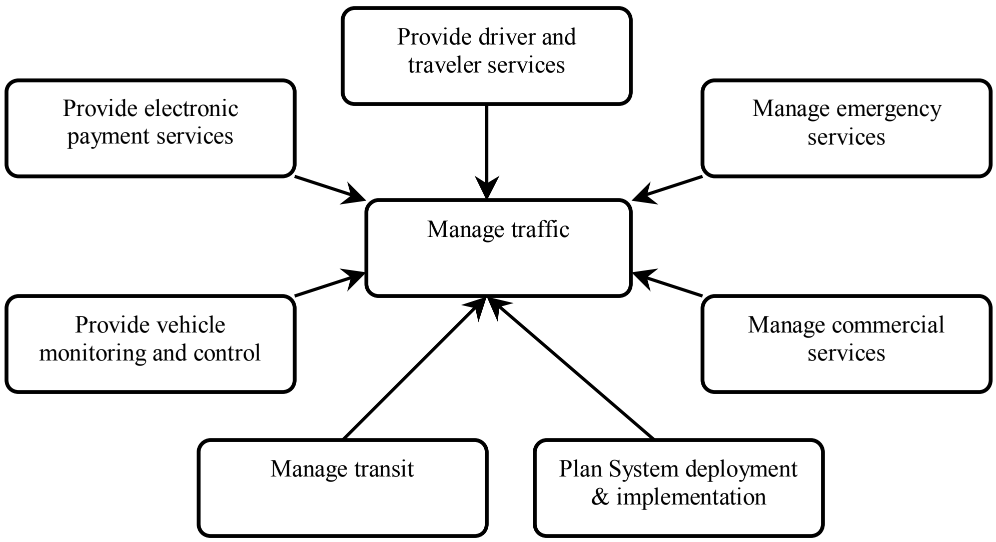

Figure 1: Eight Processes in ITS Architecture

2.2.1.3 Physical Architecture

The physical architecture provides agencies with a physical representation of how the system should provide the required functionality. It takes the processes and functions identified in the logical architecture and assign them to entities called subsystems. The development of a physical architecture will identify the desired communications and interactions between different transportation management organizations. The subsystems further interact with each other through the flow of information.

There are two layers used to describe the subsystems and the information flows. The subsystems together are grouped under transportation layer and the flows of information among the subsystems are called as the communication layer. The transportation layer shows the relationships among the transportation-management elements. It is composed of subsystems for travelers, vehicles, transportation management centers, and field devices, as well as external system interfaces at the boundaries. The communications layer provides the communication services that connect the transportation layer components with each other. This layer depicts all the communications necessary to transfer information and data among transportation entities, traveler information and emergency service providers, and other service providers such as towing and recovery.

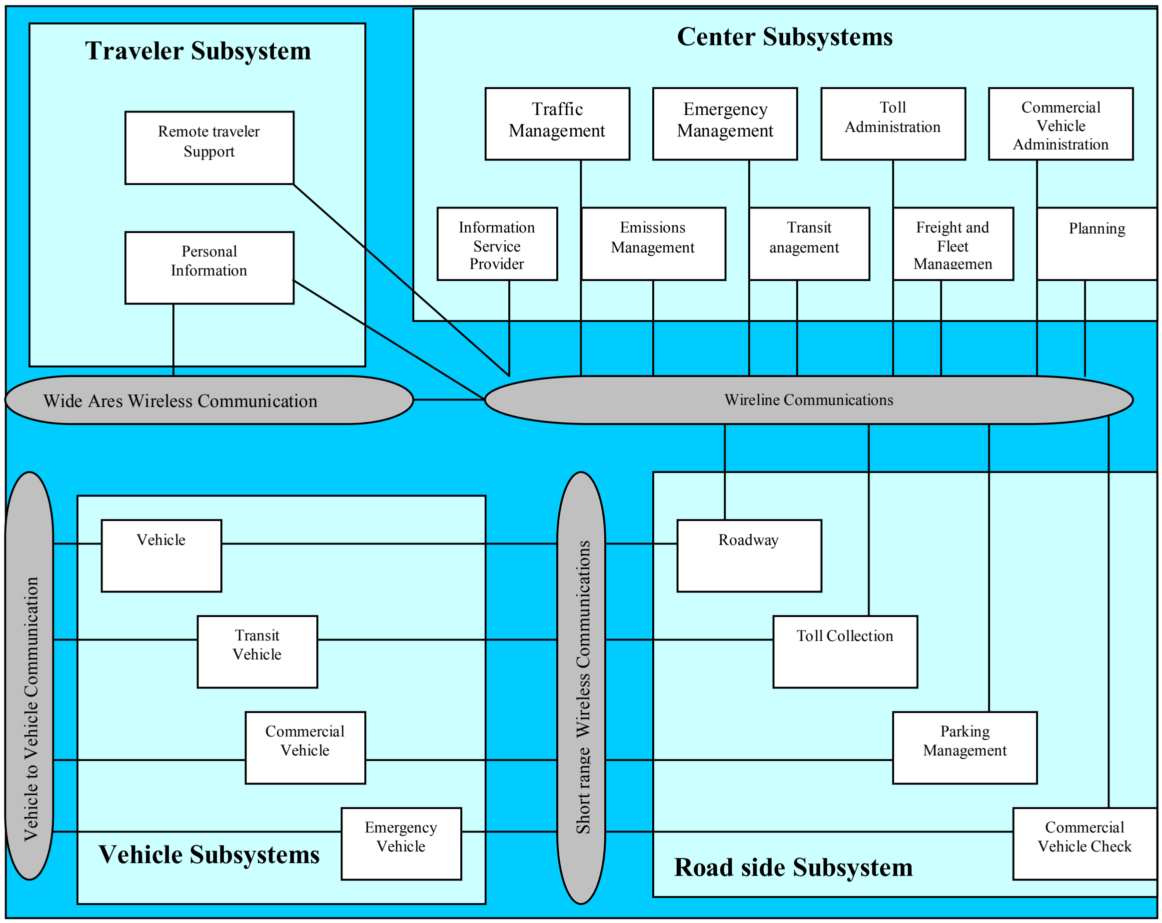

Figure 2: Transportation and Communication Layers of Physical Architecture

Courtesy: ITS America

Legends:

Transportation layer

Communication layer

Figure 2 shows the two layers of the architecture: transportation layer and the communication layer. As shown the transportation layer consists of the four subsystems: traveler subsystem, center subsystem, vehicle subsystem and road subsystem. Each subsystem consists of several components. For instance, vehicle subsystem consists of vehicle, transit vehicle, commercial vehicle and emergency vehicle. The information from these subsystems are stored in the communication layer and these information may be accessed by the other systems ensuring that there is complete flow of information.

2.2.1.5 Equipment Packages

Equipment Packages and other categorization of the architecture elements were made for better understanding and evaluation the deployment implications. The term equipment package was used in the National ITS Architecture as an effort to group like functions of a particular subsystem into an implementable package of hardware and software capabilities. Documented as part of the Physical Architecture, the grouping of functions also took into account the user services and the need to accommodate various levels of functionality within them. The National ITS Architecture has defined approximately 110 equipment packages in total.

2.2.1.6 Market Packages

Market packages are defined by sets of equipment packages required to work together (typically across different subsystems) to deliver a given transportation service and the major architecture flows between them and other important external systems. Most market packages are made up of equipment packages in two or more subsystems. Market packages are designed to address specific transportation problems and needs. It can be related back to the various user services and their more detailed requirements.

This architecture helps to find the loopholes in ITS implementation and help its deployment. It is clear that the current roads need to be utilized to the maximum capacity and one of the ways to do that is to implement Electronic Toll Collection system instead of the manual toll collection. The vehicles need not stop at the toll plaza and toll amount is automatically deducted from the radio tag fixed in the vehicle. Thus the throughput is increased without actually building additional facilities. The details are discussed in the next section.

2.3 Introduction to Electronic Toll Collection

Electronic toll collection system is used as a technology for fast and efficient collection of toll at the toll plazas. This is possible as the vehicles passing through the toll plaza do not stop to pay toll and the payment automatically takes place from the account of the driver.

The electronic toll lanes are set up with the special antennas that continuously send out signals. These signals are used to automatically identify the vehicles that travel by them. To use the electronic toll facility, the driver needs to set up an account and get an electronic transponder fixed in the vehicle. These transponders commonly known as the tags are usually fitted on the windshields of the vehicles. The tag has all the information regarding the patron’s account. The antenna continuously sends out a radio-frequency (microwave) pulse, which returns only when it hits a transponder. These pulses are returned back from the transponder and are received by the antenna. These microwaves reflected from the tags contain information about the transponder’s number, patron’s account, balance, etc. Other information such as date, time, and vehicle count could be recorded depending upon the requirement of the data needed by the toll agencies. After encrypting the contents of this microwave, the unit then uses fiber-optic cables, cellular modems or wireless transmitters to send it off to a central location, where computers use the unique identification number to identify the account from which the cost of the toll should be deducted. ETC system uses diverse technologies for its working.

Figure 3 shows the working of the electronic toll collection system with its components. These components may vary depending upon the technology used. As the vehicle enters the toll lane, sensors (1) detect the vehicle. The two-antenna configuration (2) reads a transponder (3) mounted on the vehicle's windshield. As the vehicle passes through the exit light curtain (4), it is electronically classified by the treadle (5) based on the number of axles, and the ETC account is charged the proper amount. Feedback is provided to the driver on an electronic sign (6). If the vehicle does not have a transponder, the system classifies it as a violator and cameras (7) take photos of the vehicle and its license plate for processing. The components of ETC are discussed in the next section.

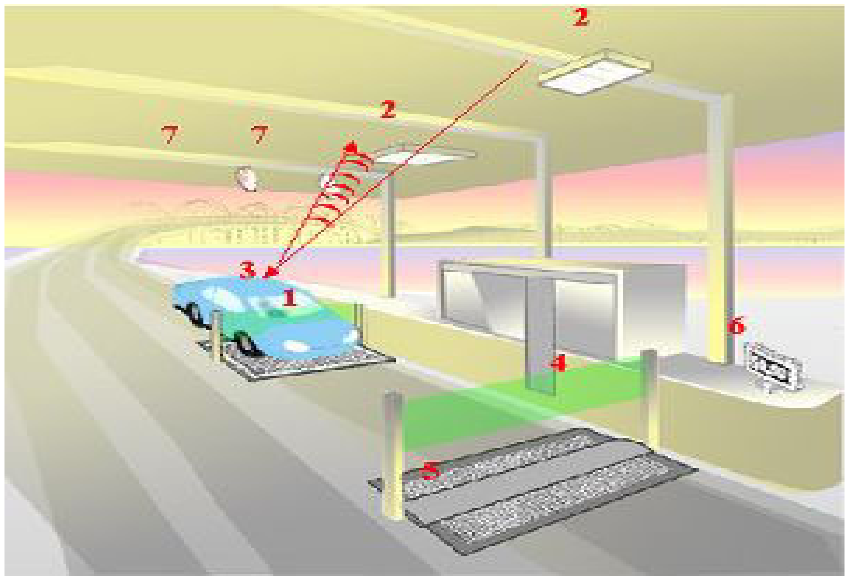

Figure 3: ETC System Operation

Courtesy: Caltrans

2.3.1 *Components of Electronic Toll Collection*

ETC systems deploy various communications and electronic technologies to support the automated collection of payment at tollbooths. Collectively, the application of these technologies increase system throughput, improve customer service, enhance safety, and reduce environmental impacts. The components of the ETC technology are as follows:

1. Automatic Vehicle Identification -- The automatic vehicle identification (AVI) component of an ETC system refers to the technologies that determine the identification or ownership of the vehicle so that the toll will be charged to the corresponding customer.

2. Automatic Vehicle Classification -- Vehicle type and class may have differentiated toll amount. The vehicle type may include light vehicles like the passenger car or heavy vehicles like recreational vehicles. A vehicle's class can be determined by the physical attributes of the vehicle, the number of occupants in the vehicle, the number of axles in the vehicles and the purpose for which the vehicle is being used at the time of classification (or some combination of these determinants). Some toll agencies use as many as 15 or more vehicle classes to assess tolls, although for ETC applications, four or five classes are more typical.

3. Video Enforcement Systems -- When used for ETC, the video enforcement system (VES) captures images of the license plates of vehicles that pass through an ETC tollbooth without a valid ETC tag.

Although the deployment of these technologies makes the initial cost of installation very high, but there exits huge benefits accompanied with such high investment. These benefits are discussed in the next section.

2.3.2 *Benefits of Electronic Toll Collection*

The benefits of the ETC include:

1. Congestion reduction -- The toll transaction rate is highly increased due to the use of ETC systems. Since the vehicles do not stop at the toll facility, the throughput is highly increased. This has considerable effect on the congestion of the toll plaza. As the proportion of the ETC users increases the congestion in the manual as well as the automatic lanes is also reduced. The average number of vehicles waiting in the queue reduces and so the average waiting time is reduced.

2. Increased Capacity -- It is observed that the capacity of the electronic lane increases by three fold. The toll plaza would be able to accommodate the increasing traffic without requiring building additional lanes.

3. Fuel saving -- The deceleration, acceleration and idling is completely eliminated. This results in gas saving for the patrons using ETC. Besides the elimination of acceleration and deceleration results in reduction of the operating cost of the vehicles.

4. Operating cost saving -- Over a period of time, the toll collecting cost is reduced. There is reduction in the man-hour required as the system does not require any human interaction for the toll transaction.

5. Time saving -- ETC users do not stop for paying toll, thus there is considerable saving in the travel time. Besides the travel time reliability is increased as the travel time can be estimated fairly accurately.

6. Emission control -- Due to the elimination of the acceleration and idling, vehicular emissions are reduced. Though this benefit only effect the surrounding area it is seen that there is an increase in the highway financing by building toll plazas. In many non-attainment areas as declared by Environment Protection Agency (EPA), ETC seems to be one of the possibilities for air pollutant reduction.

7. Enhanced cash handing -- There is no cash transaction for the ETC lane so cash handling is reduced so difficulties with cash handling is eliminated. Thus aid in enhanced audit control by centralizing user accounts.

8. Payment flexibility -- The patrons do not have to worry about searching for cash for the toll payment. Since the patrons set up account for ETC usage it gives customers the flexibility of paying their toll bill with cash, check, or even credit cards.

9. Enhanced data collection -- Information such as vehicle count over the time of the day, date, time etc can be obtained due to the deployment of this technology. This helps in making decisions regarding the pricing strategies for the toll providers. It also helps planner to estimate the travel time that aid in designing decisions.

10. Incident reduction --It is observed that there is reduction in the number of incidents caused near the toll plazas (Gillen, 1999).

With all these benefits, it is evident that there exists a lot of opportunity of research in studying the impacts of these benefits over the ETC lanes. This research will address all the quantifiable components of the benefits on the integrated basis.

CHAPTER 3

LITERATURE REVIEW

In this chapter, a systematic review of the research done in the area related to ETC is presented. In section 3.1, review of demand-supply and pricing strategies for ETC provides general information of the effectiveness and acceptability of the varying toll pricing and the effects of pricing strategies on travel demand and traffic congestion. Section 3.2 on High Occupancy Toll (HOT) lanes, reviews the high occupancy toll lanes specific to the application of ETC. In section 3.3, a review of the techniques for the evaluation of the ETC projects is done. Section 3.4 presents the individual benefits of ETC system. Finally, in section 3.5, research area for simulation, used in evaluation of the improvements of ETC, is reviewed. The above study will provide a better understanding of the research done in ETC and its applications.

3.1 Demand-Supply Model and Pricing Strategies

Demand-supply is a measure used to understand the effects of the toll pricing and varying pricing. Gifford (1996) discusses about elasticity of demand with respect to the changes in the toll amount especially with varying tolls. The finding lends empirical support to claim that time-varying prices may be a viable strategy for managing traffic demand. The implementation of such a technique is made simpler by the adoption of ETC technology.

The development of automatic toll collection technology has now made congestion pricing schemes technically feasible. Value pricing, also known as congestion pricing or peak-period pricing, entails fees or tolls for road use that vary by level of congestion. This concept of assessing relatively higher prices for travel during peak periods is the same as that used in many other sectors of the economy to respond to peak-use demands.

Road-use charges that vary with the level of congestion provide incentives to shift some trips to off-peak times, less-congested routes, or alternative modes, or to cause some lower-valued trips to be combined with other trips, or eliminated. A shift in a relatively small proportion of peak-period trips can lead to substantial reductions in overall congestion. And, while congestion charges create incentives for more efficient use of existing capacity, they also provide improved indicators of the potential need for future capacity expansion. It generates revenues that can be used to further enhance urban mobility. If properly applied, congestion pricing on roads can reduce peak period travel, save time and smooth traffic flow, resulting in positive environmental and economic benefits and this is possible by the use of ETC systems.

Burris and Swenson (1998) and Burris (2002) have done a similar kind of study on the Lee County located along Florida's southwest coast. The electronic toll users were given 50 percent discount if the patrons used the toll road on the time other than the morning and the evening peak hours. This served as an incentive for the drivers to travel outside of peak periods. It was observed that there was a change in the travel pattern due to variable pricing and the result was reduced congestion during the peak period. Determining the pricing strategy is a challenging area and much of it would depend on modeling varying tolls prices during the time of the day. Jia *et al*. (2002) developed a model for the route choice at California SR 91 to study the effect of value pricing on the toll bridge on SR 91. The results showed that adjusting the toll can significantly affect the route choice of the patrons and thus demand can be regulated.

3.2 High Occupancy Toll (HOT) Lanes

This is one of the applications that became possible due to the deployment of ETC. Thus ETC was employed at the high occupancy vehicle (HOV) lane to convert them to high occupancy toll lane (HOT). High Occupancy Vehicle (HOV) lanes were introduced to metro Atlanta on December 14, 1994, along an 18-mile section of I-20, east of I-75/85. HOV lanes are identified by diamond-shaped pavement markings and overhead signs and they are designated only for vehicles carrying two or more occupants, certified alternative fuel vehicles, motorcycles and emergency vehicles. It has been argued that at some places the HOV lanes are not fully used to its capacity. So it was suggested to convert the HOV lane to HOT lane. This opens the lane for the solo drivers who will be allowed to use the lane by paying some toll and it would be still toll-free for the high occupancy vehicles. The variable pricing can be applied to the HOT lanes to restrict the solo drivers from using the lane in the peak period and this is also possible by using ETC on the HOV lanes. Lari and Buckeye (1999) discuss that the excess capacity of the HOV lanes can be overcome by opening it to all drivers. This can be done by requiring the single occupancy vehicle to pay for the usage of the HOV lanes. The problem of general public acceptance was also discussed. It was observed that public acceptance increases when HOT lanes are presented in the context of the system. It means that the benefits obtained from the single occupancy vehicle (SOV) patrons can be used for the maintenance of the roads that would increase the efficiency of the current resources.

3.3 Cost-Benefit Analysis

During the early stages of the research, in 1993, an attempt was made to study the benefits of the electronic toll and traffic management by Pietrzyk and Mierzejewski (1993). Halloran (1992) did similar work for evaluating the working of ETC and its benefits. During that period, there was no fully integrated ETTM systems in operation so an effort was made to synthesis of emerging technologies and its application were discussed. The study intended to provide information on the ETC to the transportation agencies so that evaluation and decision making processes may be more informed and productive. The characteristics of the different technologies available in 1993 were taken into consideration such as inductive loop systems, active and passive RF/Microwave systems, optical systems, surface acoustical wave and their relative advantages and disadvantages were discussed. This research helped the transportation agencies to decide upon the technologies that can be used depending the requirement of the systems. The research gives good analysis regarding the flow rate considering the lanes to be mixed, dedicated or express lanes and corresponding capacity of the toll bridge was calculated.

The implementation issues were also discussed with the complete money transaction of manual as well as of ETC and thus bring out the cash handling benefit due to ETC implementation. Certain privacy issues were also discussed and the cost of ETC set up was analyzed for each lane. Though the benefits mentioned gave good information about the possible outcomes of the implementation of the technology the question of measuring and quantifying those benefits relating to the users and the community was still unanswered. But it was shown that an effort was made by some of the transportation agencies to measure the performance of the ETC.

Gillen et al. (1999) develops a methodology to calculate the cost and the benefits of the ITS projects. The various components of costs and benefits were evaluated and cost-benefit analysis was carried out to check the effectiveness of the project. Peng *et al.* (2000) developed a methodology by using breakeven analysis to evaluate the benefits of the ITS projects. The breakeven analysis was used to screen, prioritize and select ITS projects among different ITS options. It gives an estimate of the assumptions required to calculate the benefits. Turner *et al*. (1998) did similar studies on developing the ITS benefits. A methodology was developed for all the ITS components and so it could be used to study the effect of any components individually.

The previous studies were done in determining methodologies that would give estimates of the effectiveness of the ITS projects. Basically, costs were calculated in each of the methodology and then the benefits were estimated. Using financial tools, the ITS projects were then evaluated. The financial tools or methods may be benefit-cost ratio method, rate of return method, net present value method and annual cost method.

Gillen *et al*. (1999) extended the methodology to access the benefits of ETC systems. The study gave an extensive account of the ETC cost its benefits. The methodology was used by Caltrans to test the ETC project on the Carquinez Bridge. Estimates were provided for each fiscal year between 1995-1996, and between 2005-2006. For year the 2000-2001 the time saved for toll transactions was estimated at 2,153 hours for ETC versus tickets, and estimated at 3,533 for ETC versus cash transactions. Also, the time saving for movement through the toll facility was estimated at 19,500. The results indicated a total timesaving of 25,193. Using assumed fuel consumption rates, fuel savings were estimated at 55,425 gallons (per year) or $60,968 per year in 1995 dollars. The report also estimated a person-time savings of 79,919 hours (per year) or about $1.07 million. Emission reductions were estimated at 9.82 million grams of CO, 1.06 million grams of NOx, and 0.46 million grams of HC (per year). The emissions reductions were translated into a cost reduction of $1,998. Real world data from the report indicated that the total number of accidents increased between 1996 and 1997 from 27 to 30. Personal injures increased from 5 in 1996 to 13 in 1997. It was clearly evident that the ETC deployment will certainly benefit the transportation agencies, users and society.

3.4 Benefit Modeling

There has been a considerable amount of work done is evaluating the benefits of the ETC system. Al-Deek et al. (1997) discussed about the operation benefits of electronic toll plazas at the Orlando-Orange County Expressway Authority. The findings indicated that for the dedicated ETC lane, the measured capacity is tripled, the service time has decreased by five seconds per vehicle and maximum queuing delay has decreased by 2.5 to 3 minutes per vehicle. This indicates that the benefits are huge but it depends on the time it would be required to convert the manual lanes to electronic lane.

Levinson (2003) developed a model to maximize the social welfare associated with the toll plaza. He develops a payment choice model that estimates the share of traffic using ETC as a function of delay, price and a fixed cost of acquiring a transponder. The delay depends on the number of the electronic lane and the manual lane. If the number of the electronic toll is increased the delay at the manual will be increased to a large extent. The price depends on the discount given to the users of the ETC lanes. The cost of acquiring the transponder is not only monetary but also an effort is involved in signing up for the program. Levinson assumed that the welfare depends on the share of the ETC, and includes delay and gasoline consumption, toll collection costs, and social costs such as air pollution. The study examines the best combination of ETC lanes and the toll discount to maximize welfare. The model developed was applied to California Carquinez Bridge to study its effect.

The application of the queuing simulation model to the electronic toll was studied by Zarrillo *et al.* (1998) for modeling the delay or the waiting time at the electronic toll for the rush hours and also studied the effect of the various parameters on the capacity of the toll plaza. Fambro and Rouphail (1997) modeled the delay at the signalized intersection and these models are applied to estimate the delays at ETC. But there were limitation as these models were developed for signalized intersection. The time difference due to the deceleration and acceleration and its elimination were not accounted in the study. Sisson (1995) discusses about other benefits like air quality benefits or mobile emissions reduction.

3.5 Simulation Studies

Various simulations models are used to quantify the benefits of ETC. Saka *et al.* (2001) used microsimulation to model the traffic operation and quantify the impacts of electronic toll. It is clearly evident that a large benefit can be achieved due to the deployment of the ETC and the sooner the ETC systems are deployed, the sooner the benefits can be realized.

According to the above research it is shown that electronic toll collection can reduce congestion, reduce travel time, smooth traffic flow and decrease air pollution, resulting in positive environmental and economic benefits. The benefits can be increased if and only if ETC can be employed as soon as possible and are made available to more people.

Simulation model such as MOBILE by U.S. Environment Protection Agency (EPA), EMFACs by California Air Resource Board (CARB), and CALINE by California Department of Transportation (Caltrans) are used to estimate the mobile emissions. Most of the emissions models estimate the components such as carbon monoxide (CO), hydrocarbon and nitrogen oxide (NOX) as these are major contributors of the mobile emissions. Pesesky and Marin (1990) used MOBILE4 to estimate CO, NOX, and HC emissions under different Automatic Vehicle Identification (AVI) applications scenarios at New Jersey Turnpike Interchange. In this research, the emissions factor produced by previous studies are used to estimate vehicle emissions. Some of the studies are shown the results as shown below.

Table 1 shows emissions values from 1989-1994 of previous work by Cicero-Fernandez and Long (1993), and 1988 and older by Sisson (1995). Table 2 gives the emissions rate of all vehicles (Kirchstetter, et at. 1998). The values used in this research are taken by Kirchstetter, *et at*. (1998) for the estimation of the benefits of ETC.

Table 1: Grams Emitted per 0-65 Acceleration by Car Age

Car age	Pollutants		
	CO	NO_X	HC
1989-1994	33	0.75	0.95
1980-1988	196	2.36	7.07
1979 and older	686	7.20	25.41

The value of the emission reduction can be determined in many ways. One of the methods is to determine on the basis of the amount of economic or health damages caused by pollution (Small and Kazimi, 1995). According to Small and Kazimi, the unit costs of health damage are as shown in the table below. Another method is to determine the value on the basis of costs to remove the pollutants. Wang and Santini, (1993) determined the unit costs based on the cost of replacing typical gasoline powered cars with electric vehicles. The values provided by Illinois EPA were based on the costs of buying older, higher polluting cars and destroying them. The unit estimates of Bernard and Thorpe were taken from studies of railroad electrification for emissions reductions. This research uses the average costs of health damage provided by Small and Kazimi since the effects of mobile emissions are more tangible to daily life.

Table 2: Emissions Rate of All Vehicles

	Pollutants		
	NO_X	HC	CO
Acceleration Emissions Rates (grams/gallons)	24.7	9.5	209
Idle Emission Rate	--	0.1~0.2	2~3

The value of the emission reduction can be determined in many ways. One of the methods is to determine on the basis of the amount of economic or health damages caused by pollution (Small and Kazimi, 1995). According to Small and Kazimi, the unit costs of health damage are as shown in the table below. Another method is to determine the value on the basis of costs to remove the pollutants. Wang and Santini, (1993) determined the unit costs based on the cost of replacing typical gasoline powered cars with electric vehicles. The values provided by Illinois EPA were based on the costs of buying older, higher polluting cars and destroying them. The unit estimates of Bernard and Thorpe were taken from studies of railroad electrification for emissions reductions. This research uses the average costs of health damage provided by Small and Kazimi since the effects of mobile emissions are more tangible to daily life.

Table 3: Cost Estimates of Air Pollution

($/Kg of pollutant)

Source	Pollutant		
	CO	NO_X	HC
Wang and Santini	0.00	27.84	22.69
Bernard and Thoroe	1.10 3.04	8.21 3.04	6.70 3.63
Small and Kazimi	0.0063	1.22~1.33	1.22~1.33
Value used in the study	0.0063	1.28	1.28

In this chapter we discussed about the various areas of application of ETC systems and estimation of its benefits. As seen from the review, most of the study involved computation of the benefits on the individual basis. Studies done for the integrated benefits were aimed at evaluating the effects of ETC for a particular toll plaza.

CHAPTER 4

PROBLEM STATEMENT

In this chapter, the problem addressed by this research is discussed in detail. In addition, the assumptions made in developing the model for the ETC system are described. Finally, the research objectives are discussed.

4.1 Problem Description

It is evident that toll plazas are usually the bottlenecks for highway traffic flows. For this congestion problem one alternative will be to build additional lanes. However, this option requires a huge investment. According to Al-Deek (1997), with the use of ETC the throughput of the system can be increased three times. For that reason, ETC systems might represent a more feasible alternative than building additional toll lanes.

One of the key factors for all the ETC projects is to calculate the benefits that it might produce before the actual implementation. There is a dearth of research done in integrating all the benefits for ETC. Previous studies show that the benefits for ETC are evaluated on an individual basis. In addition, since most of these projects are relatively new, the benefit analysis has been done with less accuracy.

The system considered consists of arriving vehicles, toll lanes and vehicles leaving the system. The lanes can be characterized into five basic types: manual, automatic (exact change or coin operated), mixed electronic toll, dedicated electronic toll (within a conventional plaza), and express electronic toll lanes. Manual toll lanes require all toll transactions to be handled by a toll collector. Automated lanes collect tolls by providing coin machines. Mixed ET lanes combine ET with toll collection system that is manual, automatic, or both. Dedicated ET lanes are contained within conventional toll plazas but permit ETC patrons only. Express ET lanes are physically separated from all other type toll lanes permitting free-flow (nearly 50 miles per hour or greater) speeds.

This research integrates all the benefits associated with ETC and develops a model for the economically quantifiable benefits. Some of the questions that will be answered include finding right time for ETC implementation, determining it's economic feasibility for the current traffic flow for a given toll plaza, and determining the effect of the number of ETC lanes on the benefits. The answers to these questions are needed before ETC systems are implemented given the huge investment required.

The economically quantifiable benefits considered while developing the model are the user and community benefits. The users benefited by ETC system include: daily commuters, non-regular users and users for business or personal purposes. Since toll plazas are located at many places, the community will also benefit from the installation of ETC by reduction of mobile emissions that will impact the air pollution. Besides the number of non-attainment areas as specified by the Environment Protection Agency (EPA) are increasing and ETC could be an answer to this problem to some extent. But these benefits mentioned largely depend on the market share of the ETC users. Accurate estimation of the benefits will help to decide upon strategies required by the toll agencies for its successful implementation.

4.2 Assumptions

Following are the assumptions made in modeling the benefits of the ETC systems. These assumptions are based on previous studies.

1. The service time for the ETC lanes is estimated to be 2.4 seconds. The service time for the manual lanes and exact change lanes is estimated to be 8 seconds (Zarrillo, 1997).
2. Three types of lanes are considered: manual, automatic (coin) and ETC.

3. The share of manual and automatic toll transactions are 75% and 25% respectively.
4. The ETC transaction is 5% in the first year of implementation and then increased at a rate of 5% per year over the lifespan of the project.
5. The traffic flow is increased at a rate of 3% annually.
6. The internal rate of return (IRR) is assumed to be 5%.

4.3 Research Objectives

The objectives of the research are as follows:

1. To integrate all the benefits for ETC.
2. To model these benefits of ETC over the manual toll collection system.
3. To determine the financial value of the benefits produced over the life span of the project.
4. To study the effects of the number of the ETC lanes and other traffic parameters over the benefits.
5. To disseminate research to serve as a guideline for the transportation agencies for making decisions.

The model developed can be used at any toll plaza to evaluate the performance and behavior of ETC under various traffic flows. Since this research models the benefit before the actual implementation of ETC, benefits such as reduction in operation and maintenance costs are not covered in the study. However, modeling the user and community benefits would be of considerable interest to the DOT's, policy planners and transportation agencies.

CHAPTER 5

MODEL DEVELOPMENT

In this chapter a model that incorporates all the quantifiable benefits for user and society as a whole has been developed.

5.1 Introduction

In this chapter a model that incorporates all the quantifiable benefits for user and society as a whole has been developed. The inputs for the model are Average Annual Daily Traffic (AADT) and number of lanes of the toll plaza including the lane type. Initially a single dedicated electronic lane is allocated by converting one of the automatic or manual lane into ET lane. The benefit is calculated for the single ET lane and then the number of ETC lanes is increased depending upon the delay at the ETC lanes. shows details of calculation for the user and community benefits. After the parameters are inputted in the model, time saving, gasoline saving and emissions are calculated. The total benefit is then computed and its financial value is determined. The cash flow for the lifetime of the project is computed along with its present value. This gives the complete estimate of the user and community benefits.

The steps for the estimating the benefits of the ETC and its financial value over the lifetime of the project follow

1. The model requires the following inputs from the user: number of lanes for the toll plaza and traffic flow rate. Given the input, the arrival rate is calculated and then the vehicles are allotted to the manual, exact change or electronic lanes depending upon the

probability of usage of these lanes. Then the number of vehicles using the ETC is estimated along with the estimate for the manual and the exact change lane.

2. The model requires the following inputs from the user: number of lanes for the toll plaza and traffic flow rate. Given the input, the arrival rate is calculated and then the vehicles are allotted to the manual, exact change or electronic lanes depending upon the probability of usage of these lanes. Then the number of vehicles using the ETC is estimated along with the estimate for manual and automatic lane.

3. Then factors for savings such as: deceleration elimination, waiting time reduction, service time reduction, and acceleration elimination are calculated. Then the total time saving is calculated based on all the factors discussed. The gasoline saving is calculated due to elimination of acceleration. During deceleration, the vehicle engine uses very less amount of gas hence gasoline saving due to deceleration is neglected. Emission reduction is computed due to reduced waiting and servicing time and elimination of acceleration. The waiting time at the electronic toll lanes is zero as the vehicles using ETC do not stop at the toll bridge to pay the toll.

4. The financial value of the benefit is calculated annually depending upon the travel time cost, gasoline cost and emission reduction cost.

5. The traffic flow is then increased at a rate of 3 % for the next year and the whole procedure of calculating the benefits for the next year is repeated for 10 years to calculate the total benefit. The financial value of the benefit over the lifespan of project is then calculated.

6. The present value of the amount is calculated using the time valuation method with internal rate of return as 5%. However this could be varied to include the effect of inflation.

7. The financial value of the benefit is calculated annually depending upon the travel time cost, gasoline cost and emission reduction cost.

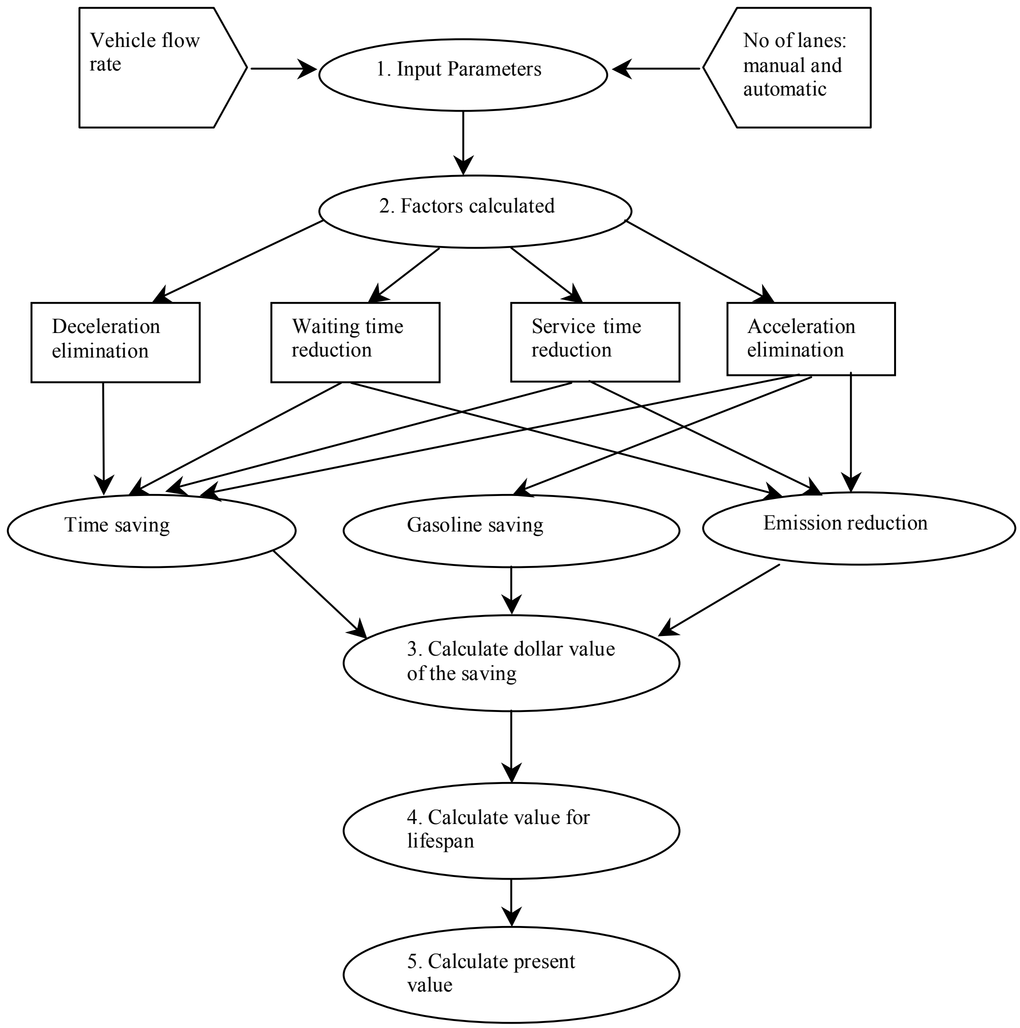

Figure 5: Model for Benefit Calculation of ETC

8. The traffic flow is then increased at a rate of 3 % for the next year and the whole procedure of calculating the benefits for the next year is repeated for 10 years to calculate the total benefit. The financial value of the benefit over the lifespan of project is then calculated.

9. The present value of the amount is calculated using the time valuation method with internal rate of return as 5%. However this could be varied to include the effect of inflation.

5.2 An Integrated Benefit Model

The model in the most generalized form is as follows:
Total financial value of benefits = Travel time value (T_V)* total time saving (T_S) + gasoline cost (G_C) * gasoline saving (G_S) + emissions reduction cost (E_C)* amount of emissions reduction (E_S).

FINANCIAL BENEFIT (B) = T_V*T + G_C * G_S + E_C * E_S

Figure 6 gives the various components of the benefit model. Each components of the benefit model are discussed in the following sections. Section 5.2.1 deals with determining the value of travel time followed by detailed description of the model component, time saving, in section 5.2.2. In section 5.2.3, gasoline saving is modeled along with estimation of its financial value. Section 5.2.4 deals with modeling the emissions reduction and then developing NPV model in the section 5.2.5 to estimate the present value of the future benefits.

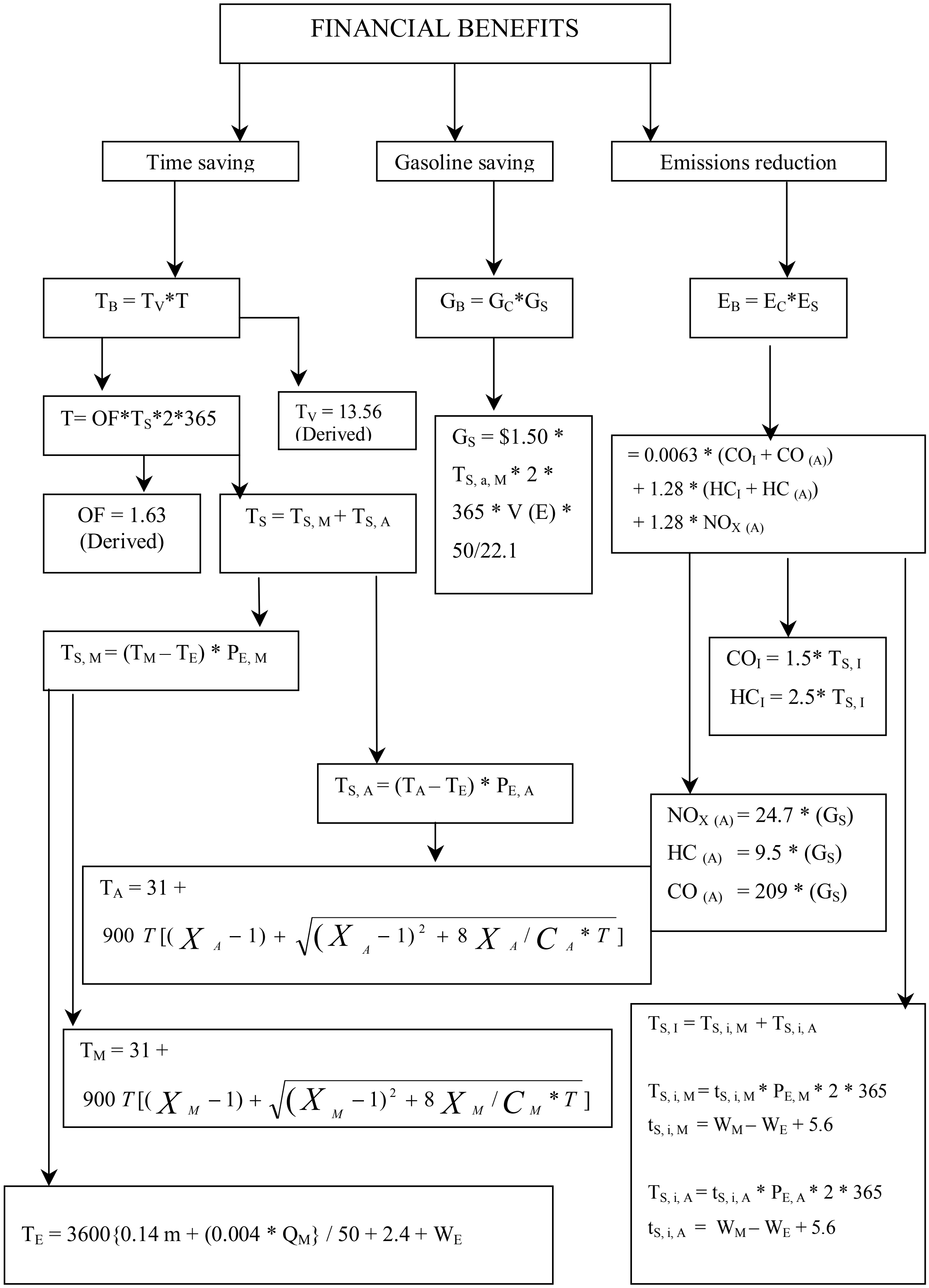

Figure 6: Model Components

5.2.1 *Travel Time Value*

The value of time saving depends upon many factors including transportation mode, trip purpose (business or personal), income, trip type (local or intercity), etc. In 1997 DOT published a memorandum to assist analysts in developing consistent evaluations of actions that save or cost time in travel. The values recommended are as shown in the Table 5. The travel time value of the passengers in the passenger cars is taken to be same as the value of the passengers of the buses. For example the travel time value for personal intercity travel is $14.80 for both passengers traveling in passenger cars or buses.

Value of travel time (T_V) = Average value of travel time of persons in car * proportion of the passenger car + average value of travel time of persons in buses * proportion of the buses + average value of travel time of person in car truck * proportion of the trucks.

The proportion of the vehicles is as discussed in the Table 4 and the values recommended for the travel time are taken from the Table 5.

Table 4: Vehicle Distribution

	Passenger cars	Buses	Trucks	Total
Number of motor vehicles	221,821,103	749,548	7,857,674	230,428,325
% of the total vehicles	96.26	3.41	0.33	

Value of travel time factor (T_V) = 13.4 * 0.9626 + 13.4 * 0.0033 + 18.10 * 0.0341

$$T_V = 13.56$$

Table 5: Value of Travel Time

Recommended Hourly Values of Travel Time Savings (2000 U.S. $ per person-hour)		
Category	Surface modes	Trucks
Local Travel		
Personal	$10.60	--
Business	$21.20	--
All Purpose	$11.20	$18.10
Intercity Travel		
Personal	$14.80	--
Business	$21.60	--
All Purpose	$15.60	$18.10
Average Values	$13.4	$18.10

5.2.2 *Total Time Saving*

The travel time saving is defined as follows:

Total time saving (T) = vehicle occupancy factor (OF) * travel time saving (T_S) * number of peak hour considered (2 hours for current study) * number of days (365, if the input is AADT and 260 if the input is AAWT, for the current research, it is considered for AADT).

T= OF * T_S * 2 * 365

5.2.2.1 *Vehicle occupancy factor (OF)*

The vehicle occupancy factor is used to determine the total time saved on an individual basis depending upon the vehicular distribution. Vehicle occupancy factor estimates the average occupancy for each vehicle. The occupancy factor can be obtained by two parameters: proportion of the vehicle type, and average occupancy of that vehicle type.

First, the vehicle distribution is estimated for determining the proportion of the passenger cars, buses and trucks as shown in the Table 4 according to the statistics from FHWA. Second, the vehicle occupancy estimated by determining the ratio of the total person-miles and total vehicle-miles as shown in Table 6.

Table 6: Person and Vehicles Miles

Miles	Passenger cars	Buses	Trucks
Person-miles of travel (millions)	4,066,046	148,113	207,686
Average miles traveled per vehicle	11,528	9,320	26,431
Number of motor vehicles registered	221,821,103	749,548	7,857,674
Average Occupancy	1.59	21.20 ~ 21	1

Average Occupancy factor, OF = Average occupancy of passenger car * proportion of passenger cars + Average occupancy of buses * proportion of buses + Average occupancy of trucks * proportion of trucks

Average Occupancy factor, OF = 1.59 * 0.9626 + 21 * 0.0033 + 1 * 0.0341

OF = 1.63

5.2.2.2 *Travel Time Saving*

The travel time saving for the total passenger time saving annually is calculated as below.

Travel time saving (T_S) = $T_{S,M} + T_{S,A}$

$T_{S,M} = (T_M - T_E) * P_{E,M}$

$T_{S,A} = (T_A - T_E) * P_{E,A}$

$T_S = (T_M - T_E) * P_{E,M} + (T_A - T_E) * P_{E,A}$

Where $T_{S, M}$ = Travel time saving at the manual lane

$T_{S, A}$ = Travel time saving at the automatic lane

T_M = Total time for manual transaction

T_A = Total time for automatic transaction

$P_{E, M}$ = Proportion of the vehicles that would have used manual if not ET lane

$P_{E, A}$ = Proportion of the vehicles that would have used automatic if not ET lane

The Directional Design Hourly Volume (DDHV) accounts for the total traffic during the peak hour period. DDHV is calculated using the formula:

DDHV = AADT * K * D

DDHV = Directional Design Hourly Volume

AADT = Average Annual Daily traffic

K = the proportion of the daily traffic occurring during the peak hour

D = the proportion of peak hour traffic traveling in the peak direction

The K and D factors usually are computed based upon the local and regional characteristics at existing locations (McShane and Roess, 1998). In general, the K factor decreases as the density of development surrounding the highway increases. The D factor depends upon the development density and upon the specific relationship of the facility in question to major traffic generators in the area.

Table 7: Peak Hour and Peak Direction Factor

Facility Type	Normal range of factors	
	K Factor	D Factor
Rural	0.15-0.25	0.65-0.80
Suburban	0.12-0.15	0.55-0.65
Urban: Radial route	0.07-0.12	0.55-0.60
Urban: Circumferential route	0.07-0.12	0.50-0.55

Assumption: The values for K and D considered are 0.12 and 0.60. The higher values are considered to take into account the maximum effect of the traffic demand during the peak period.

The number of vehicles using ET lanes, V (E) = 0.05 * DDHV

$P_{E, M} = 0.75 * V (E)$

$P_{E, M} = 0.75 * 0.05 * DDHV$

$P_{E, A} = 0.25 * V (E)$

$P_{E, A} = 0.25 * 0.05 * DDHV$

Transaction Time at Manual (T_M) Calculation

The total time spent in the system is the sum of the deceleration time, waiting time, toll processing time and the acceleration time to the average speed. The total for each of lane type can be estimated as follows. The acceleration time estimation is shown in the next section.

T_M = Deceleration time (D_T) + average waiting time (W_M) + average service time at manual lane (T_T) + acceleration time to normal speed (A_T).

$T_M = D_T + T_T + W_M + A_T$

- Deceleration Time (D_T) Calculation

The time spent for the deceleration is the sum of the perception-reaction time and the braking time to come to stop at the toll plaza for toll transaction or stop and join the queue for the toll transaction. The American Association of state highway and transportation officials (AASHTO) recommends the use of 2.5 seconds perception-reaction time in computations involving stopping or braking reactions. The total deceleration distance required before actually stopping the vehicle is given as follows:

Stopping distance (d_S) = perception-reaction distance (d_p) + braking distance (d_b)

$d_S = d_p + d_b$

$d_p = 1.468vt = 1.468 * 50 * 2.5 = 183.5$ ft

$d_b = (v^2 – u^2) / 30(f + g)$

$d_b = (50^2 – 0^2) / 30(0.31+0) = 268.82$ ft

Where v = speed of vehicles (mph)

t = perception-reaction time (sec)

1.468 = conversion factor from mph to fps

v = initial speed of the vehicles (mph)

u = 0, final speed of vehicles (mph)

f = 0.31, coefficient of forward rolling or skidding friction

g = 0, assumed to be level terrain

30 = unit conversion factor

$d_S = 183.5 + 268.8 = 453$ ft = 0.09 miles

The deceleration rate is 3.86 mph/sec for the given condition of stopping and the deceleration time or the time required to stop at the tollbooth or to stop to join the queue is calculated as follows:

$v = u + a * D_T$

$D_T = 50/3.86$

$D_T = 13$ seconds

The deceleration time is 13 seconds for the stopping at the toll plaza.

➢ Toll Transaction Time (T_T) Calculation

The processing time for manual and automatic is taken to be nearly 8 seconds per transaction (Zarrillo, *et al*. 1998) and the processing rate for ET lane is 2.4 seconds. The time for ET lane is the headway and it is defined as the time taken between consecutive vehicles arriving at a particular point for the same point of reference on the vehicle. The processing rate is calculated as following.

$\mu_M = \mu_A = 450$ (vehicles per hour, vph)

$\mu_E = 1500$ (vehicles per hour, vph)

Where μ_M = average manual processing rate

μ_A = average automatic processing rate

μ_E = average ETC processing rate

➢ Waiting time (W_M) calculation

The waiting time for each lane is determined using the delay model presented in Highway Capacity Manual (2000). In general, delay can be categorized into three main types: random delay, toll transaction delay, and delay due to acceleration and deceleration. The random delay is due to the stochastic nature of arrivals. When the vehicle arrival is higher then the service capacity during the peak period, they must wait to pay toll. The delay model in HCM is developed to estimate delay for the signalized or unsignalized intersection. This model offers some perspective for estimating the waiting times at the toll plazas. Modification is made to the general model to calculate the delay at the toll plaza. The waiting time or delay is calculated for each lane per lane type using the formula:

$$W = 900\,T[(X - 1) + \sqrt{(X - 1)^2 + 8X / C * T}]$$

Where W = incremental, or random, stopped delay (seconds/vehicle),

X = volume to capacity ratio of lane group,

C = capacity of lane group (vehicles/hour),

T = Time for consideration, peak period, (hours).

The model developed is used separately for estimating the waiting time at the manual, automatic and electronic lanes.

$$W_M = 900\,T[(X_M - 1) + \sqrt{(X_M - 1)^2 + 8X_M / C_M * T}]$$

Where W_M = Average waiting time in minutes for manual lane

X_M = volume to capacity ratio of manual lane,

C_M = capacity of manual lane (vehicles/hour),

T = Time for consideration, peak period, (hours).

- Acceleration Time (A_T) Calculation

For estimating the total time for acceleration to road speed of 50 mph, the average acceleration is assumed to be 5mph/sec (Homburger, *et al.* 1982) and the acceleration time (A_T) to reach to road speed from complete stop is 10 seconds.

Form the above estimation of the parameters, the total time at the manual is given as follows:

$T_M = 13 + 8 + W_M + 10$

$T_M = 31 + W_M$

Transaction Time at Automatic (T_A) Calculation

The total time at the automatic is calculated in the same way as for the manual. It is estimated as follows:

T_A = Deceleration time + average waiting time + average service time at automatic lane + acceleration time to normal speed.

$T_A = 13 + W_A + 8 + 10$

$T_A = 31 + W_A$

The waiting time (W_A) at the automatic is given by

$$W_A = 900T[(X_A - 1) + \sqrt{(X_A - 1)^2 + 8X_A / C_A * T}]$$

Where X_A = volume to capacity ratio of automatic lane,

C_A = capacity of automatic lane (vehicles/hour),

T = Time for consideration, peak period, (hours).

Transaction Time at ETC (T_E) Calculation

The time taken to cover the accelerating distance, waiting distance, toll transaction and acceleration distance is the total time for electronic transaction. For ETC lane, the vehicles do not stop so there is elimination of the deceleration and acceleration. Thus the deceleration and acceleration distance along with the waiting distance are covered at the average road speed. The average car length for the design purpose is taken to be 19ft (Homburger, *et al.* 1982)

Distance covered (D) = Distance covered during deceleration + Average length of queue * Average length of passenger car + distance covered during acceleration

$D = 0.09\ m + 19/5280 * Q_M + 0.05$

Distance covered $(D) = 0.14\ m + 0.004 * Q_M$

Average queue length, Q_M = vehicle arrival rate * Average waiting time at the manual

$$Q_M = \lambda_M /3600 * W_M$$

Arrival rate at the manual, λ_M is calculated as follows:

Based on the previous studies and observations made at the Orlando Orange County Expressway Authority (OOCEA), the percentages of the manual and the automatic toll lane users are assumed to be 75% and 25% respectively.

V (E) = 0.05 * DDHV

V (M) = 0.75 * 0.95 * DDHV

V (A) = 0.25 * 0.95 * DDHV

Where V (E) = number of vehicles using ETC lanes

V (M) = number of vehicles using Manual lanes

V (A) = number of vehicles using Automatic lanes

After the numbers of vehicles are allotted to each type of lane for manual, automatic and ETC, the vehicles are then divided equally for each lane type. The vehicle flow rate per lane for each lane type is same. This is due to the fact that as the driver approaches the toll plaza there is a tendency to choose the lane with lowest number of vehicles waiting in the queue, thus equalizing the number of vehicles waiting in the queue and thus reaching equilibrium in terms of vehicular flow rate. The numbers of vehicles are determined using the following equation:

Number of vehicles per lane per hour is given as follows:

$$\lambda_M = \frac{V\ (M)}{m}, \quad \lambda_A = \frac{V\ (A)}{a}, \quad \lambda_E = \frac{V\ (E)}{e}$$

Where λ_M = number of vehicles arrival per manual lane per hour,

λ_A = number of vehicles arrival per manual lane per hour,

λ_E = number of vehicles arrival per manual lane per hour,

m, a, e are the number of manual, automatic, and electronic lanes respectively.

T_E = Distance covered (D) /average speed + toll transaction time (headway) + W_E

The time for ET transaction is the headway and it sits defined as the time taken between two consecutive vehicles arriving at a particular for the same point of reference on the vehicle. The headway is taken to be 2.4 seconds. Thus the processing rate (μ_E) is 1500 vph.

The waiting time (W_E) at the ET lane is given as follows:

$$W_E = 900\,T[(X_E - 1) + \sqrt{(X_E - 1)^2 + 8\,X_E / C_E * T}\,]$$

Where X_E = volume to capacity ratio of automatic lane,

C_E = capacity of automatic lane (vehicles/hour),

T = Time for consideration, peak period, (hours).

Transaction time at manual (T_E) considering all the parameters is determined as follows:

$T_E = 3600\{0.14\ m + (0.004 * Q_M\} / 50 + 2.4 + W_E$

5.2.3 *Gasoline Savings*

With the elimination of the deceleration, waiting, and acceleration there is a considerable amount of gas savings. The acceleration of the vehicles consumes major of the gas and the gas consumed is very less during deceleration and waiting for the toll transaction.

Thus the gas used during the deceleration and waiting is neglected. The time saved due to acceleration at manual is same as that at automatic since the vehicles come to complete stop in both the cases. The total gas saving is given is estimated as follows:

Number of gallons saved (G_S),

G_S = Total time saving due to elimination of acceleration ($T_{S, a, M}$)* road speed for the ET lane / average miles traveled per gallons.

$G_S = T_{S, a, M} * 2 * 365 * V(E) * 50\text{mph} / 22.1 \text{ mpg}$

$T_{S, a, M}$ = Acceleration time – distance covered during acceleration / average speed

As discussed in the previous section, the accelerating time (A_T) is 10 seconds and the distance traveled (A_D) to the average road speed is calculated as follows:

$v^2 = 2 * a * A_D$

$A_D = 50^2 / 2 * 5$

$A_D = 250$ ft

$A_D = 0.05$ miles

The distance traveled (A_S) to the average road speed is 0.05 miles.

$T_{S, a, M} = A_T - A_D$ / average road speed

$T_{S, a, M} = 10 - (0.05/50) * 3600 = 10 - 3.6$

$T_{S, a, M} = 6.4$ seconds

Cost of gasoline (G_C) is assumed to be \$1.50 per gallon

Total financial value of the gasoline saved = Cost of gasoline per gallons (\$1.50)* total number of gasoline saved

Total financial value of the gasoline saved (G_B)= $\$1.50 * T_{S, a, M} * 2 * 365 * V(E) * 50/22.1$

5.2.4 *Emissions Reduction*

Mobile emissions are the result of the deceleration, vehicle idling and acceleration. Since very less gas is used when decelerating, mobile emissions are negligible during deceleration. The major components of the mobile emissions are carbon oxides (CO), nitrogen oxides (NO_X), and hydrocarbon (HC) during vehicle idling and acceleration. Previous studies as discussed in the literature review show that there are various methods for estimating the mobile emissions.

The time saving for idling is due to the reduction of waiting time and toll transaction time at the ET lane. The time saving is calculated for each vehicles and the total time saving for the proportion of vehicles using ETC system is estimated. In this study the waiting in the queue is considered to be idling as the vehicles moves very slowly with many frequent stops.

During idling of the vehicles the NO_X is negligible as compared to CO and HC (Kirchstetter, *et at*.,1998). In this research, the mobile emissions are estimated using the study done by Kirchstetter, *et at.* (1998). The financial values are evaluated using the study done by Small and Kazimi (1995).

The total annual idling time saving, ($T_{S, I}$) is the sum of the idling time saving at the manual, $T_{S, i, M}$ and at the automatic, $T_{S, i, A}$

Total annual idling time saving, $T_{S, I} = T_{S, i, M} + T_{S, i, A}$

Vehicle idling time saving for the manual per vehicle, $t_{S, i, M} = (W_M + T_T) – (W_E + 2.4)$

$t_{S, i, M} = (W_M + 8) – (W_E + 2.4)$

$t_{S, i, M} = W_M – W_E + 5.6$

Total idling time saving for the manual, $T_{S, i, M} = t_{S, i, M} * P_{E, M} * 2 * 365$

Vehicle idling time saving for the automatic per vehicle, $t_{S, i, A} = (W_A + T_T) – (W_E + 2.4)$

$t_{S, i, A} = W_M – W_E + 5.6$

Total idling time saving for the automatic, $T_{S, i, A}$ =, $t_{S, i, A}$ * $P_{E, A}$ * 2 * 365

Amount of CO saved due to idling reduction, CO_I (grams) = 1.5* $T_{S, I}$

Amount of HC saved due to idling reduction, HC_I (grams) = 2.5* $T_{S, I}$

Emissions reduction due to acceleration elimination due to the gasoline saved as calculated as follows.

$NO_{X\ (A)}$ (grams) = 24.7 grams/gallons * number of gallons of gasoline saved.

$NO_{X\ (A)} = 24.7 * (G_S)$

$HC_{(A)} = 9.5 * (G_S)$

$CO_{(A)} = 209 * (G_S)$

Where $NO_{X\ (A)}$ = NO_X reduction due to elimination of acceleration or gasoline savings

$HC_{(A)}$ = HC reduction due to elimination of acceleration or gasoline savings

$CO_{(A)}$ = CO reduction due to elimination of acceleration or gasoline savings

The emissions cost is used from the study done by Small and Kazimi (1995) and the value suggested is \$0.0063 /Kg for CO, \$1.28 /Kg for HC and \$1.28 /Kg for NO_X.

Total saving (E_B) = 0.0063 * CO saved + 1.28 * HC saved + 1.28 * NO_X saved

$$E_B = 0.0063 * (CO_I + CO_{(A)})/1000 + 1.28 * (HC_I + HC_{(A)})/1000 + 1.28 * NO_{X\ (A)}/1000$$

5.2.5 *NPV Modeling*

The benefit model developed is used to estimate the projected value of the financial benefits for the project life of the project. A NPV model is developed to find the present value of these projected benefits. Since the benefits are considered at the end of the year the model is based on the present value of the annuity. The general equation used to find the present value of an ordinary annuity is shown below

$$\text{NPV} = \sum_{j=1}^{j} \frac{B_j}{(1+i)^j}$$

Where NPV = Present value

B_j = Benefit for each year

i, j = Discount rate and Project life of ETC (10 years)

CHAPTER 6

RESULTS AND ANALYSIS

In this research an integrated benefit model has been developed to calculate the financial value of the benefits for the toll plazas with different number of toll lanes and with variable traffic flow. The deployment of the ETC system not only increases the capacity of the toll plaza but also reduces the total delay caused at the manual and the automatic lanes. It is seen that the benefit largely depends of the operating traffic level of the toll plaza and the ETC share. As the traffic flow increases on the toll plaza the delay increases.

The benefit model has been evaluated for different instances of traffic flow and toll plazas with various lane configurations. Specifically the model is tested for 5 to 8 lanes toll plaza as this represents major percentage of the existent toll plazas in the nation where ETC systems are deployed. During the peak hours of operation, the vehicle flow rate may be much higher than the capacity of the toll plaza. To account for these and other conditions, the effect of the traffic flow is studied from design capacity to more than 100 % increase.

6.1 Conversion to ETC Lanes

For a given toll plaza, there are two ways of installing the ETC lanes. One is to convert lanes from the manual or automatic and the other one is to have additional lanes. This research evaluates both the cases. For each of the cases, three scenarios have been considered:

Scenario 1—Initially, at year 1 the benefit is estimated with the traffic flow to be at the maximum design capacity level and then it is increase by 3% annually. The maximum design capacity is defined as the maximum number of vehicles that the toll plaza can process depending upon the total number of lanes. For design purposes, the number of vehicles that can be processed for each lane is nearly 450 vehicles per hour for manual as well as for automatic lanes (Zarrillo, 1997).

Scenario 2 – The second scenario assigns 30% higher traffic flow @ year 1 than design capacity and is further increased by 3% annually.

Scenario 3 – The third scenario assigns 70% higher traffic flow @ year 1 than design capacity and is further increased by 3% annually.

Table 8 and Figure 5 shows the benefits for a 5 lane toll plaza with 3 manual (M) and 2 automatic (A) lanes in the year of ETC deployment, automatic lane is converted to ETC lane as 25% of the traffic is routed to these automatic lanes. Typically the manual lanes handles 75% of the traffic flow. For that reason, installing ETC systems at the manual lanes will cause higher delays. Table 9 and Figure 7 shows that the benefit for 5 lanes after increasing the number of ETC lanes in year 5.

From Table 8 it is seen that for all scenario nearly at the 5th year of ETC implementation the benefit begins to fall and reaches a negative value towards the end of the project life. At that point of decrease in the benefit, it is recommended to convert another lane to ETC lane.

The numbers of ETC lanes are increased depending upon the saturation level of the ETC lanes. The saturation level is the ratio of the vehicle arrival to the processing rate of the toll plaza. For higher level of service the processing rate should be higher than the arrival rate. As the arrival rate increases the waiting time or the delay for the toll transaction increases. It is observed that the benefits fall when the degree of saturation reaches a value higher than 0.5. For example the NPV value for the benefit is nearly $2.91 M for the 5 lanes toll plaza for scenario 1. This value increases to $11.4 M for scenario 2 and further to $28.1 M for scenario 3, as the ETC share increases along with the increase in the traffic flow.

As shown in Table 8 and Table 9 for the scenario 1, the benefit is $2.91 M for one ETC installed throughout the project life. Besides, if the numbers of ETC lanes are increased as recommended in table 9 the value of the benefit increases to $10.3 M. There is an increase in the benefit for the scenario 2 and scenario 3. As observed for scenario 2, for the toll plaza with single ETC lane, the benefit value is $11.4 M and with two ETC lanes as recommended in Table 9, the benefit is $28 M.

Table 8: Benefit for 5 Lanes Toll Plaza with One Converted ETC Lane

Years	Lane Configuration					
	M	A	E	Scenario 1	Scenario 2	Scenario 3
1	3	1	1	193230	637962	1492890
2	3	1	1	351173	1234890	2939554
3	3	1	1	467527	1766643	4303773
4	3	1	1	532077	2209865	5544678
5	3	1	1	545927	2539242	6631121
6	3	1	1	511464	2734031	7444904
7	3	1	1	446478	2740432	7109835
8	3	1	1	371621	2399033	4555062
9	3	1	1	284767	587202	397257
10	3	1	1	16857	(2582918)	(5487492)
NPV				2916315	11465718	28141705

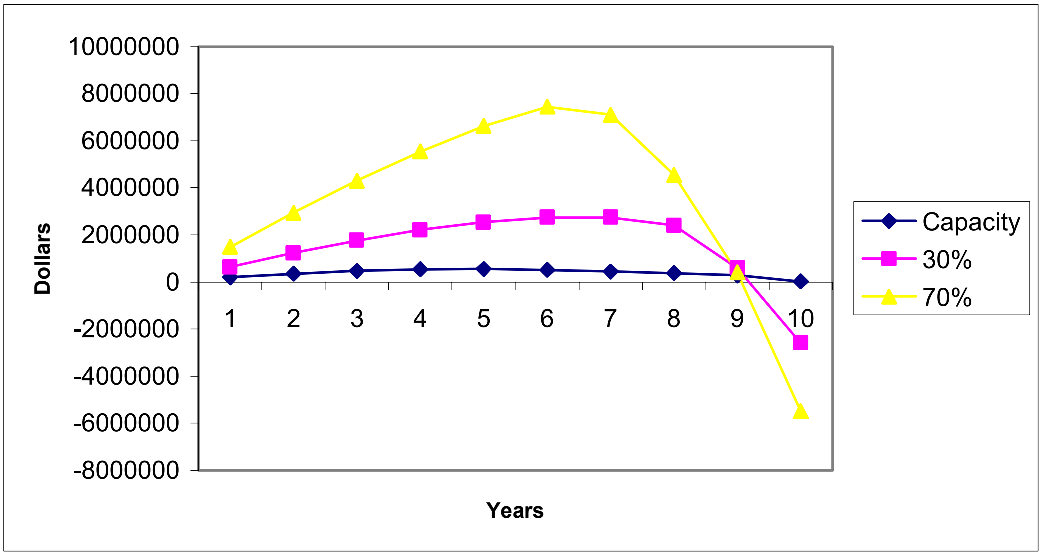

Figure 7: Benefit for 5 Lanes Toll Plaza with One Converted ETC Lane

Table 9: Benefit for 5 Lanes Toll Plaza with Multiple Converted ETC Lane

Years	Lane Configuration					
	M	A	E	Scenario 1	Scenario 2	Scenario 3
1	3	1	1	193230	637962	1492890
2	3	1	1	351173	1234890	2939554
3	3	1	1	467527	1766643	4303773
4	3	1	1	532077	2209865	5544678
5	3	1	1	545927	2539242	6631121
6	2	1	2	2532366	2751430	13443588
7	2	1	2	2661760	6951710	15014912
8	2	1	2	2661036	7297042	16216392
9	2	1	2	2524129	7351065	16919322
10	2	1	2	2212409	7051980	17038758
NPV				10339660	28048798	70608287

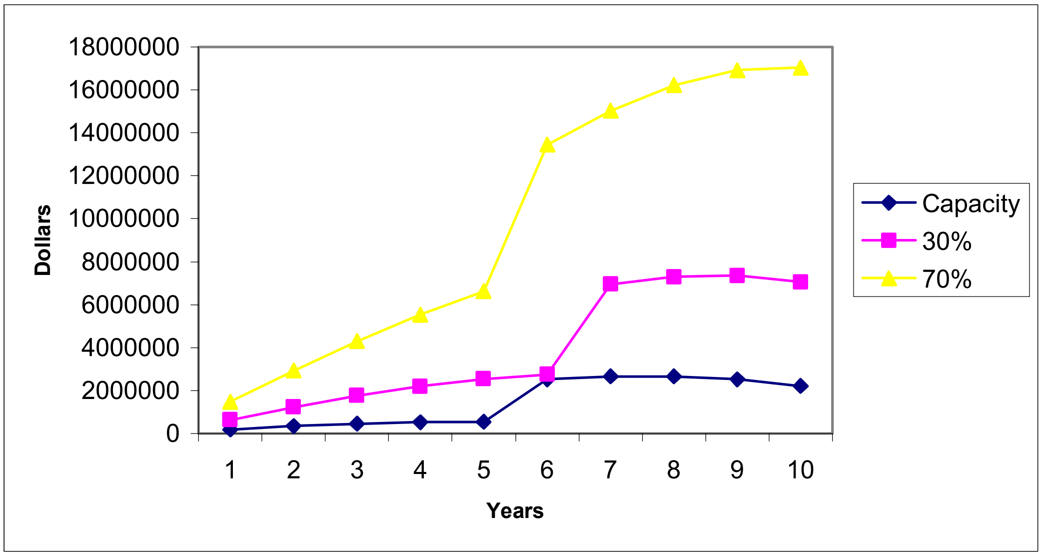

Figure 8: Benefit for 5 Lanes Toll Plaza with Multiple Converted ETC Lane

6.2 Addition of ETC Lanes

In the previous section, one of the manual or automatic lanes were converted to the ETC lane and then depending upon the delay and degree of saturation, the number of ETC lanes were increased by further converting manual or automatic lanes. In this section, for a given toll plaza, the benefits are evaluated for the toll plaza by assuming additional lanes. Thus the numbers of manual or automatic lanes are not affected. Table 10 to Table 13 gives the benefit for using additional ETC lanes for a given toll plaza. The numbers of ETC lanes are increased depending the degree of saturation at the ETC lanes and the traffic flow. The scenarios considered are just as in the previous section and the corresponding benefits are evaluated.

Table 10: Benefit for 5 Lanes Toll Plaza with Multiple Additional ETC Lanes

Years	Lane Configuration					
	M	A	E	Scenario 1	Scenario 2	Scenario 3
1	3	2	1	147054	477568	1125829
2	3	2	1	267871	924911	2210748
3	3	2	1	358047	1325056	3228177
4	3	2	1	410252	1658338	4151583
5	3	2	1	424847	1906602	4953491
6	3	2	2	408286	2072974	5635316
7	3	2	2	368531	2106717	6105104
8	3	2	2	327154	1998805	6341447
9	3	2	2	296308	1734233	6272840
10	3	2	2	274005	1328766	5838721
NPV				2509933	11627181	33626840

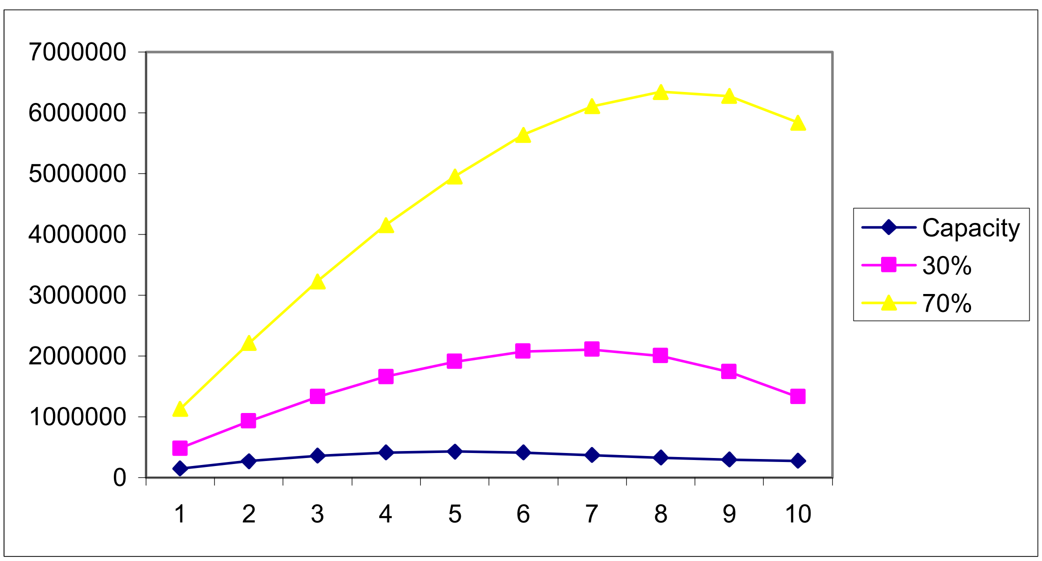

Figure 9: Benefit for 5 Lanes Toll Plaza with Multiple Additional ETC Lanes

Table 11: Benefit for 6 Lanes Toll Plaza with Multiple Additional ETC Lanes

Years	Lane Configuration					Lane Configuration			
	M	A	E	Scenario 1	Scenario 2	M	A	E	Scenario 3
1	4	2	1	100719	436289	4	2	1	1180983
2	4	2	1	177439	826072	4	2	1	2301384
3	4	2	1	227359	1159678	4	2	1	3321983
4	4	2	1	255657	1414151	4	2	1	4207583
5	4	2	1	263349	1571041	4	2	2	4956894
6	4	2	2	271614	1642347	4	2	2	5484010
7	4	2	2	271119	1571853	4	2	2	5770523
8	4	2	2	269274	1379987	4	2	2	5781011
9	4	2	2	266405	1087459	4	2	3	5557114
10	4	2	2	262097	783845	4	2	3	4923683
NPV				1780185	9019795				32138218

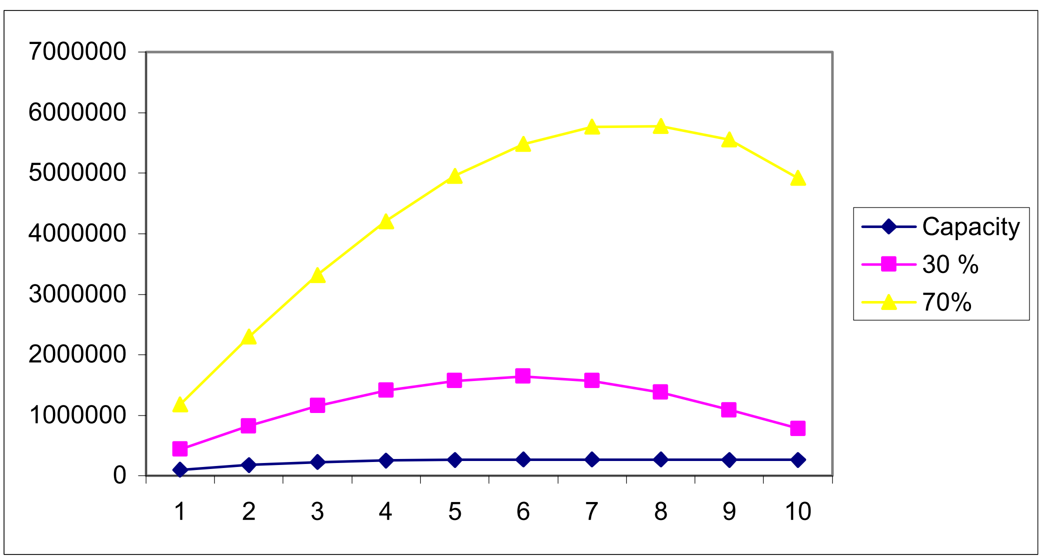

Figure 10: Benefit for 6 Lanes Toll Plaza with Multiple Additional ETC Lanes

Table 12: Benefit for 7 Lanes Toll Plaza with Multiple Additional ETC Lanes

Years	Lane Configuration					Lane Configuration			
	M	A	E	Scenario 1	Scenario 2	M	A	E	Scenario 3
1	4	3	1	254623	754453	4	3	1	1703659
2	4	3	1	472419	1466391	4	3	1	3353332
3	4	3	1	642048	2105283	4	3	1	4916145
4	4	3	1	752516	2660184	4	3	1	6332330
5	4	3	1	795097	3076687	4	3	2	7649105
6	4	3	1	778587	3407568	4	3	2	8706214
7	4	3	2	697786	3521903	4	3	2	9478423
8	4	3	2	587789	3415866	4	3	2	9836233
9	4	3	2	490738	3108307	4	3	3	10021371
10	4	3	2	414092	2518050	4	3	3	9535536
NPV				4512983	19373643				52318007

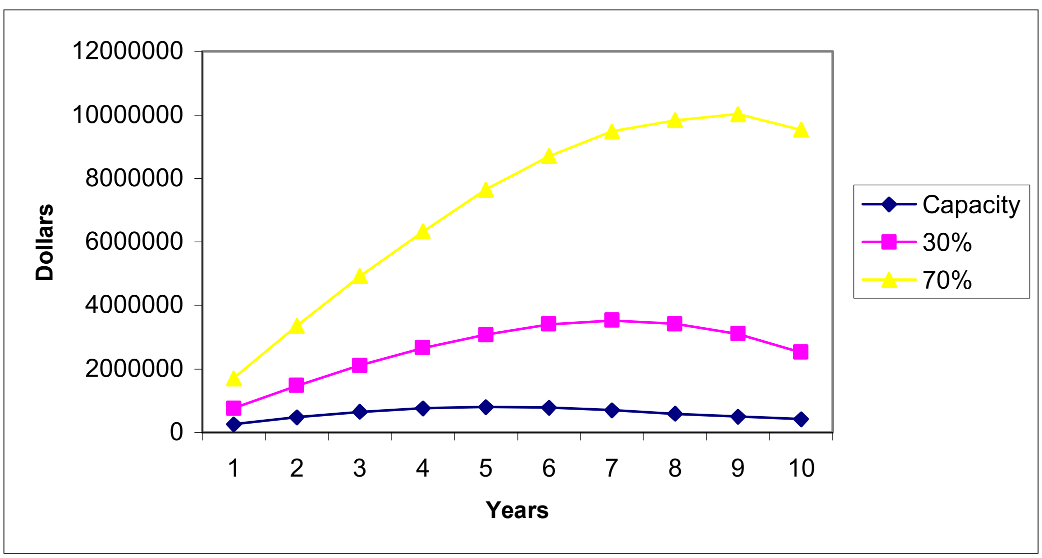

Figure 11: Benefit for 7 Lanes Toll Plaza with Multiple Additional ETC Lanes

Table 13: Benefit for 8 Lanes Toll Plaza with Multiple Additional ETC Lanes

Years	Lane Configuration					Lane Configuration			
	M	A	E	Scenario 1	Scenario 2	M	A	E	Scenario 3
1	5	3	1	193339	688669	5	3	1	1703153
2	5	3	1	345915	1323832	5	3	1	3326020
3	5	3	1	452612	1882128	5	3	1	4827814
4	5	3	1	506103	2329345	5	3	2	6197212
5	5	3	2	523437	2678002	5	3	2	7353563
6	5	3	2	500953	2850410	5	3	2	8249567
7	5	3	2	464417	2827273	5	3	3	8908270
8	5	3	2	426021	2578997	5	3	3	9152621
9	5	3	3	416806	2196539	5	3	3	8922356
10	5	3	3	398137	1625634	5	3	3	8065751
NPV				3220687	15792908				49054317

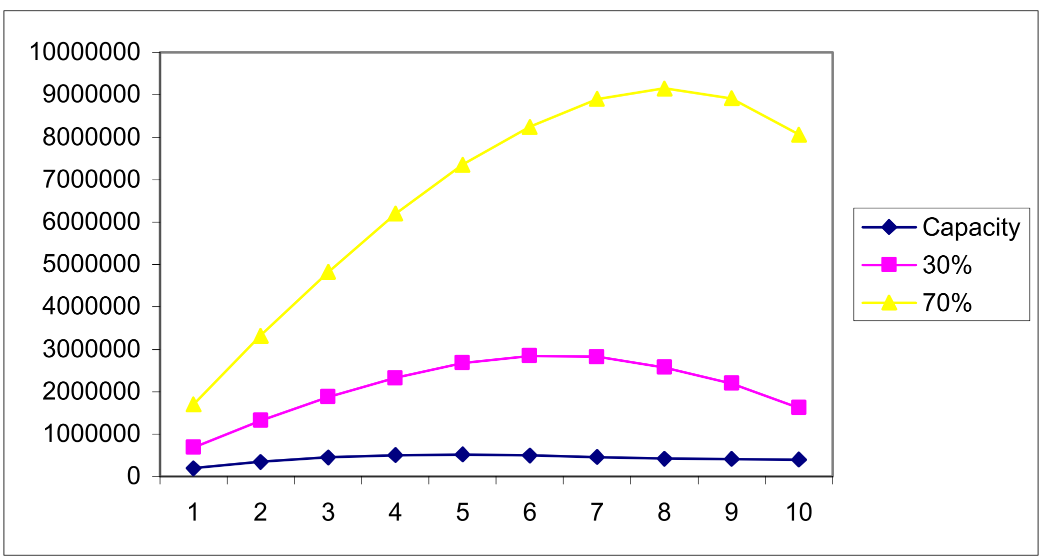

Figure 12: Benefit for 8 Lanes Toll Plaza with Multiple Additional ETC Lanes

In the above chapter, the value of the benefit is determined for toll plazas with different number of lanes. In one case, one of the automatic or the manual lane is converted to ETC lane and the corresponding benefit is estimated. The model helps to estimate the time for the deployment of the ETC to maximize the benefits and also recommends the number of ETC lanes to maximize the benefits for the given toll plaza based on the delay and the saturation level. The effect of the traffic flow rate is also considered for the model development.

The other case for the benefit for the ETC estimation is when an ETC lane or lanes are added to the current toll plaza. The point of increasing the number of ETC lanes is also estimated. It is seen that the second case with additional ETC lanes, the value of the benefits are consistent and the number of lanes do not affect the delay at the manual or automatic. As the ETC share increases, the delay at the manual and automatic decreases.

CHAPTER 7

CONCLUSION

7.1 Concluding Remarks

In this research, a model that integrates all the quantifiable benefits for the ETC system based on the established assumptions has been developed. In addition, the effect of the number of ETC lanes on the total benefits has been analyzed. This offers some perspective into number of ETC lanes that need to be deployed in order to maximize the benefit. In addition, the benefit is estimated for the project life of the ETC.

A model is developed to estimate the total benefits of the ETC system over the manual and automatic. The model helps in analyzing the time for the ETC deployment depending the benefits.

The values for the benefits of the users are overestimated to an extent, as the model does not take into account the cost component for the user such as the cost of acquiring the transponder and the opportunity cost.

A number of conclusions can be drawn from this study. The estimation of the benefit largely depends on the established assumptions. Thus there is a certain limitation to the accuracy of the model. The values of the assumptions may change to certain extent from region to region. Though the values used are national averages, better estimate can obtained by using more region specific parameters.

It has been observed that major benefits are the time and gasoline savings. Other benefit such as mobile emissions are produced but with small magnitude. The estimation of the travel time saving largely depends on the delay model used to estimate the waiting time. Models developed for toll plaza would certainly help the benefit model to give more accurate results. Besides the above mentioned benefits, ETC increases travel convenience. Hence ETC definitely provides improved level of services to its users. The model suggests initially deploying single ET lane for any toll plaza and increasing the number of ET lanes with the increase in the degree of saturation of the ET lane. The number of ET lanes can be increased when the degree of saturation at the ET lanes increases more than 0.5. It is seen that the value of the benefit falls when the degree of saturation for the ET lanes increases to a value higher than 0.5.

Since ETC system is to be deployed over next years after the initial implementation; this helps in the distribution of the initial high capital cost along the project life of ETC system. Thus reducing the initial high investments.

With increase in the ETC share, the average delay at the manual and automatic decreases thus improving the level of service for these lanes as well.

7.2 Scope for Future Research

Some extensions that can be made to this research are as follows:

1. Incorporate accidental benefits

The model developed in the research models the user and the social benefits. Though these are the major benefits, incorporation of other benefits like the reduction in incidents at the toll plaza due to the ETC implementation would give a more comprehensive benefit model.

2. Incorporate the value of the increased reliability due to the ETC system

The reliability of the travel time is increased due to the ETC deployment and it has an impact on the value of travel time. The estimation of this factor would give better estimate of the travel time savings.

3. Study the effects of other delay models on the travel time and delay estimation

Delay model used for this research was from the Highway Capacity Manual 2000. A model more specific to toll plaza would give better estimate for the waiting times at the manual and automatic lanes.

4. Develop a dynamic system for ETC conversion

In the current research, the number of ETC lanes and their time of implementation are decided based on the delays at the ETC lane and the value of the benefits. Thus an algorithm can be developed to decide upon the optimum number of ETC lanes as compared to the manual and automatic lanes and also take into account the lane type that needs to be converted in order to maximize the benefits and reduce the delays at the toll plaza.

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