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Abstract

This paper examines the deployment of electronic toll collection (ETC) and develops a model to maximize social welfare associated with the toll plaza. A payment choice model estimates the share of traffic using ETC as a function of delay, price, and a fixed cost of acquiring the in-vehicle transponder. Delay in turn depends on the relative number of ETC and Manual Collection Lanes. Price depends on the discount given to users of the ETC Lanes. The fixed cost of acquiring the transponder (not simply a monetary cost, but also the effort involved in signing up for the program) is a key factor in the model. Once a traveler acquires the transponder, the cost of choosing ETC in the future declines significantly. Welfare, which depends on the market share of ETC, includes delay and gasoline consumption incurred by travelers, costs to the toll agency, and social costs such as air pollution accruing to society. Finding the best combination of ETC Lanes and toll discount maximizes welfare. Too many ETC lanes cause excessive delay to non-equipped users. Too high a discount costs the highway agency revenue needed to operate the facility. The model is applied to California's Carquiñez Bridge. We conclude by recommending the pace of deployment of ETC on the bridge in terms of the number of dedicated ETC lanes and the appropriate ETC discount

Introduction

Newly deployed electronic toll collection (ETC) systems enable bridge, tunnel, and turnpike operators to save on staffing costs while reducing delay for travelers. Such systems are not deployed instantaneously. Agencies need to familiarize themselves with the technology, while distrust and procrastination cause many users to defer expending time or resources to acquire transponders and establish accounts. To overcome the buy-in hurdle, some fraction of the cost savings could be returned as a discount for ETC users to optimize the use of the lanes, leaving everyone better off. Furthermore, in the absence of automatic vehicle identification and associated legislation, ETC will not be universal because a fraction of first time users must be accommodated. The intent of this paper is to inform decisions that tolling agencies must make regarding discounting tolls, obtaining a transponder, and dedicating lanes to ETC. This paper therefore tackles the question of how quickly lanes should be converted to ETC and what discount for using ETC would be socially optimal, extending previous research (Al Deek et al 1997, Burris and Hildebrand 1996, Friedman and Waldfogel 1995, Hensher 1991, Lin and Su 1994, Sisson 1995, Zarillo et al 1997).

However asking such questions is much easier than answering them. We need to develop a model for dynamic optimization over a wide choice set. For instance, we want to determine what share of the initial reluctance to switch to electronic tolls is fixed with the individual, what share depends on exposure, and what share is simply random. An agency s decision to deploy ETC lanes in one year will inevitably shape the market environment it faces in the next.

This paper begins by discussing deployment theory and the interrelationship of technology and demand. A dynamic payment choice model, describing how users choose between manual and electronic tolls is proposed. Society s benefits and costs and users payment choice, which vary with demand and the number of ETC lanes, are needed to determine the best combination in the optimization exercise. The welfare maximization model is applied to the Carqui ez Bridge case and a series of sensitivity analyses, varying the key model parameters, are performed. Finally, some conclusions are drawn about the pace of deployment of electronic toll collection.

Deployment Theory

Electronic toll collection can be considered a network in the financial and communication sense of the word. Electronic transactions take place between nodes: transponders and collection points, both tied back to the rest of the financial network. Electronic toll collection, like many complex networks, entails economies of scope, joint and common costs, spillovers, externalities, and cross-subsidies. The use of an ETC system depends on decisions made by travelers and toll agencies while user demand for ETC depends on the environment, including other ETC locations. This system exhibits several sources of positive feedback.

One source of positive feedback is network externalities: a network becomes more valuable the more members (users, destinations, etc.) it has. In principle, a single transponder may be used for multiple toll plazas and parking garages. Additional uses become increasingly viable the more uses and users that already exist, and make acquiring a transponder that much more valuable. Recently, transponders have been used at drive-through windows for fast food and for gas at service stations. Incompatible adjacent systems add unnecessary costs and decrease overall ETC share, while compatible systems following the same standards exhibit positive network externalities.

The longer a system is deployed, and the more users it has, the more confidence a non-user will have in it. They trust others' judgement that the system is reliable (it doesn t overcharge or violate their privacy), that it works, and that it is easy to use. Furthermore, the more users, the more opportunities for learning exist. A non-user will be more likely to take a ride with a user as the number of users increases and as time progresses. This learning will decrease the predisposition against ETC. Also, the longer the system is around, the more opportunities a potential user has to choose the system. Everyday a potential user has some probability of telephoning to sign up, the more days, the greater the cumulative likelihood of a call.

A related source of positive feedback is the process of cumulative causation and historical path-dependence. The longer a particular technological path is followed, the harder it is to switch, as more and more new technologies reinforce the old; technology adoption decisions have assumed a certain market environment. Finally, endogenous growth creates market niches and opportunities as the network expands, which reinforce that growth. The success of ETC deployment depends on these conditions.

However, positive feedback growth is not inexhaustible, diminishing marginal returns tend to set in after a point. S-Curves describe how a given technology is deployed over time, showing the gestation period, take-off, and saturation of a technology. The S-Curve shows the cumulative amount of a technology as a share of its total potential market. The theory underlying the S-curve is straightforward, and can be seen as an application of network externalities. As knowledge of a technology and realization of its benefits spreads, the rate of adoption increases. Each project acts as a demonstration to potential new users. Furthermore, the advantages to adoption may increase with the number of users if there are network or inter-firm scale or scope economies. As the technology diffuses, those who expect to attain the most benefit adopt it first. After a point, marginal returns diminish. It is expected that, after complete exposure, technology is adopted by those who gain the most, and then by those who gain less and less from it, until it is fully deployed. The life of technology may be cut short by competing technologies or because a technological problem is discovered. In the case of electronic toll collection, the theoretical maximum of users is 100% of the market. This market is constrained locally by demand for a transportation facility and globally by society s willingness to toll roads.

One underlying constraint behind technological advances in complex systems is the requirement of co-evolution," that is interdependent complementary technologies. Understanding this interdependence is critical to understanding the pitfalls of deploying a new technology or redeploying an old technology. Co-evolution is an example of the network externality phenomenon. Complex elements require the proper environment (network of related technologies) in which to work, and so cannot emerge in isolation. The environment here is defined broadly, to include the entire socio-technical system outside of the technology element in question. Electronic tolls only became viable when all of the related component technologies (including communications, electronic miniaturization, and financial) were also individually feasible in the 1990s. In economic terms, the environment needed for a technology to be viable can be considered as a hidden fixed cost of that technology.

Dynamic Payment Choice Model

The dynamic payment choice model aims to explain the share of each payment mechanism in any given year. In this model, the travel time, ideal lane configuration, optimal discount, and payment choice decision are all interdependent. Details on the benefit cost analysis and key assumptions are given in the appendix.

Payment Choice

We hypothesize that the choice of payment mechanism (manual or electronic) by travelers depends on the out-of-pocket cost of each alternative, the time associated with each alternative, and a one-time fixed cost associated with electronic toll collection. The ETC specific cost is expected to have a negative sign since travelers have to go through a non-effortless process to obtain transponders and open an ETC account. The logit functional form was chosen for its clarity of results rather than because of theoretical precepts relating to the expectations of the error distribution (Train 1986). In addition, our linear utility function implies complete substitutability between the travel time and out-of-pocket costs. We posit that individuals using manual payment re-evaluate their payment mechanism each time there is a change in circumstances (in this case growth, a change in the lane configuration, and discount policy), assumed to be once per year. Clearly, a more frequent cycle of user re-evaluation would entail a change in the model.

This model estimates payment choice among those who are presently users of manual lanes. Irreversibility in the decision is assumed, so ETC users do not switch to manual transactions. However, there is a survival rate, so that ETC users who change commutes away from the Carqui ez Bridge (because they change jobs, homes, or both) are replaced by new manual users who are then subject to choosing ETC. The model is given by:

$$S_e = \frac{e^{U_e}}{e^{U_e} + e^{U_m}} \qquad (1)$$

$$S_m = 1 - S_e$$

Where:

S_e share of ETC users

S_m share of manual lane users

U_e Utility of electronic tolls = $\alpha_0 + \alpha_1 T_e + \alpha_2 M_e$

U_m Utility of manual tolls = $\alpha_1 T_m + \alpha_2 M_m$

T_e travel time in ETC lane (min)

T_m	travel time in manual lane (min)
M_e	toll in ETC lane (dollars/veh)
M_m	toll in manual lane (dollars/veh)
α	model parameters

The baseline scenario coefficient on time was borrowed from previous studies on the sensitivity of choice to travel time (α_1=-0.03) (Ben-Akiva and Lerman 1985). From this and the value of time, we compute the coefficient on price. Using base year data and these values, we calculate an alternative specific constant. To test the model, a sensitivity analysis to various parameters was conducted, discussed in a later section.

The coefficient on price (α_2) was computed with the following expression and the assumed weighted value of time (V_T) of $17.41 per vehicle-hour in the benefit cost analysis (Li et al 1998).

$$\alpha_2 = \frac{60 \bullet \alpha_1}{V_T} = -0.1034 \tag{2}$$

However, this value of time is just a broad system average, so sensitivity analyses are performed later with different values (and consequently different values for the model coefficients). In the first year (FY97/98), the share of travelers using electronic toll collection (S_e) was 6%. Using base year traffic data we estimate a time difference between an average ETC user and manual user (T_e - T_m) of —35 seconds. Moreover, a discount of $0.15 was introduced to ETC users in the first year. We solved for the α_0 that would result in the model returning the first year values for share of ETC users (S_e) with the following expression:

$$\alpha_0 = \ln\left(\frac{S_e}{1-S_e}\right) - \alpha_1 \cdot (T_e - T_m) - \alpha_2 (M_e - M_m) = -3.08 \tag{3}$$

Notice that the magnitude of ETC specific coefficient is much greater than the other parameters. It means that a significant amount of savings in time and money is needed to overcome the hurdle to adopt ETC technology. When the savings are moderate, travelers would rather endure a slightly longer travel time than go through the process of obtaining a transponder.

Changing Dispositions toward ETC and Network Externalities

The constant (α_0) can be interpreted as a fixed cost associated with acquiring transponders, implicitly a predisposition against switching from manual to ETC. However, this disposition may not remain constant over time. There are several parallel but offsetting processes going on.

In year 1, some fraction of the population chooses to adopt ETC. These early adopters must have a smaller than average predisposition against the technology, that is their constant (α_0^{adopt}) is smaller in absolute terms. Thus those who don t adopt in the first year must have a greater than average value of the constant ($\alpha_0^{notadopt}$). In year 2, the average predisposition against adoption rises even more among those who haven t adopted (all other things equal). However, it is impossible to know from the available data how much higher the predisposition is, because there are many unknown factors affecting payment choice in addition to variations in to the constant (α_0).

However, the willingness to try ETC may increase with the rate of adoption if there exist any network externalities as suggested earlier in this paper. As noted earlier, several sources of those network externalities may explain why the more people who have transponders, the more willing non-users will be to choose ETC. The net effect of these offsetting factors is unclear, so sensitivity tests will be performed. First, we will simply reduce (α_0) from its base year value to 0 in year 20 linearly. Second, we will multiply (α_0) by the share of manual users $(S_m)^z$ (where the power term z is sensitivity variable) to see what happens to willingness to adopt as the background share of manual users decreases from 100% in the base. This models the combined effect of the network externality and individual predisposition.

Survival Rate

In our model, we make an irreversibility assumption, that an individual who has chosen ETC stays with electronic payment. However, a certain fraction of electronic payment users are lost each year because of changing commute patterns associated with retirement, moving or changing jobs. The fraction of those who stay with the same commute from year to year is dubbed the survival rate (S_R). This value is taken to be 84% based on previous research evaluating the survival of commutes between the same home and workplace (Levinson 1997). All replacements for non-survivors are placed in the pool of users who may choose their payment each year.

A revised choice model incorporating the concept of survival rate gives us the ETC market share ($S_{e,n}$) in year n as follows.

$$S_{e,n} = S_R \cdot S_{e,n-1} + \left(\left(1 - S_R\right) \cdot S_{e,n-1}\right) \cdot \frac{U_e}{U_e + U_m} \qquad (4)$$

Policy Variables: Capacity and Discount

According to the choice model, the toll agency can affect the evolution of ETC share in two ways. One is to provide a discount exclusively for ETC users, and the other is to impose congestion in the manual lanes by supplying more ETC capacity than needed and reducing the capacity of manual lanes. In our basic model, the toll agency decides the number of ETC lanes every year corresponding to the forecast ETC share that maximizes the overall social welfare, such that ETC delay is less than manual delay. However, this is myopic. By adding more ETC lanes and closing manual lanes, travelers will switch to ETC payment and ETC market share will grow. This may result in greater benefits in the end, despite deviating from the short run optimal. This issue would be eliminated if the model could solve the optimization problem simultaneously over 20 years rather than sequentially year by year. Unfortunately, an exact, non-heuristic, solution for the multi-year optimization is not possible at this time due to the size of the problem, though we will look at some less myopic strategies in the sensitivity analysis below. To illustrate the size of the problem, for 1 year we have to choose between 1 and 11 lanes (along with discounts). To optimize for 2 years, we have to choose over 11x11 lanes (the number of lanes in each year), so for 20 years in principle, we have 11^20 possible choices to optimize simultaneously (rather 11x20 in the myopic optimization). While we can make some simplifying assumptions such as irreversibility, it is nevertheless a much larger problem to solve.

Given the number of ETC lanes, annual traffic volume, and the dynamic payment model, there is an optimal discount, which maximizes the overall social welfare in any given year. For each year 2 through 20, an optimal combination of ETC lanes and discount is chosen to maximize the overall social welfare so long as the net benefit of the toll agency is non-negative. This constraint is set to encourage the toll agency to implement the ETC system.

Model System

Given the number of ETC lanes, discount policy and annual traffic volume, the ETC market share is estimated from the payment choice model. Then, the costs incurred and benefits gained for each class are calculated. An iterative procedure searches for the optimal combination of ETC lane configuration and discount policy to maximize total social welfare given the market demand function.

Figure 1 shows a flowchart that illustrates how the model system. In the initialization stage, the base year configuration of the toll plaza, survival rate, payment choice parameters, and optimal discount are all established using the initial assumptions. The equilibrium market share is computed using a grid search, establishing a market share that would return traffic delays that result in the same market share, given a discount and lane configuration. If the net present value from that configuration is better than all previous NPVs for that year, the lane configuration and discount are stored as optimal, otherwise, the previous optimal combination is retained. If the discount is not at a maximum, it is incremented, and the process is repeated. If the number of lanes for ETC is not at a maximum, the ETC lanes are incremented, and the process is repeated. At the end of a year’s trials, the information for that year is recorded, and the model is run for the next year, through year 20.

Results

This section discusses the results. However, because each assumption is critical to the results, analyses are conducted to investigate how the results depend on our premises. The sensitivity analyses scrutinize the assumptions on survival rate, value of time, the ETC specific constant, and capacity rules.

Basic Model

Historical traffic and financial data at the Carquinez Bridge in northern California are used to illustrate the procedure to determine an appropriate pace of ETC deployment and discount policy. The Carquinez Bridge was selected as the ETC pilot implementation in the Bay Area because it has sufficient capacity to accommodate current traffic (Li et al 1998). There are 12 lanes going through the toll plaza. A dedicated ETC lane has been opened to travelers with transponders since August 21, 1997. In addition, two lanes were opened for mixed ETC/Manual toll collection. Since vehicles equipped with ETC suffer delay when the driver of the leading vehicle pays the toll manually in mixed use lanes, the gains from mixed payment lanes are expected to be marginal and are thus neglected in our model. We treat mixed lanes as manual lanes in this exercise and assume that all vehicles equipped with transponders use the ETC dedicated lane only.

The optimal discount policy and pace of ETC deployment under specific assumptions made in this study are shown on Table 1. The overall net present value is about 61 million dollars. The Benefit Cost ratio for the Toll Agency is much less than 1, (0.24), indicating that the agency does not have any reason to proceed with the project if it chooses to ignore community welfare. However, for society overall, benefits greatly exceed costs (Benefit Cost ratio of 28.43, Internal Rate of Return of 51.5%), primarily because of delay reductions. Figure 2 depicts the evolution of ETC share over the 20-year analytical period for a number of scenarios regarding survival rate, the 84% survival rate is the baseline. In year 20, the model projects that ETC market share will reach 87% and there will be 8 ETC lanes for the baseline scenario. Table 2 presents detailed results for this scenario, showing how the overall NPV, ETC share, discounts, and number of lanes varies by year.

Survival Rate

In the original model, the survival rate is taken as 84%. The higher the survival rate, the more people who have chosen ETC payment will continue to use the system in the coming year. Hence, we suspect that a higher ETC share would be reached in year 20 as the survival rate increases. The evolution of ETC market share under different survival rates is shown on Figure 2 (constrained so the annual NPV of the toll agency is greater than zero).

When the survival rate is low, the operator has to provide greater incentives (time and money differential) to achieve the same level of market share as high survival rates. An interesting (unexpected) behavior emerges for low survival rates (here below 40%). The interplay of the overall welfare optimization and two constraints (the operator has non-negative revenue and the ETC lanes are always faster than the manual lanes) leads to what we might consider a complex phase change. It seems that the toll agency chooses to allocate more ETC lanes (11) to enlarge the travel time difference between the two payment choices, and this strategy brings about a higher market share in year 20 and a somewhat higher overall NPV. This strategy of using the maximum number of ETC lanes does not maximize welfare for higher survival rate cases. The comparison of NPV among different survival rate is shown on Table 2, clearly the higher the survival rate, the higher the overall market share and thus NPV.

Value of Time

In the original model, the value of time is taken as $17.41 per hr per vehicle. In this study, we test two alternative value of time, a value that is 10 times greater than, and a value 10 times less than, our original value. The change in the values of time affects the parameter on travel time in the payment choice model. When travelers have a higher value of time, they are more sensitive to the potential time saved by switching to ETC payment. It is expected that travelers would adopt the ETC system earlier, and the final ETC market share is going to be higher, the greater the value of time. The results shown on Figure 3 confirm the reasoning.

The market share under a high value of time exceeds that with lower values as shown on Table 1. Although a radically lower value of time does not harm too much to the pace of ETC adoption pace, the overall social welfare increases dramatically with the higher value of time. As in the original model, travelers accrue the majority of benefits. Notice that the toll agency also recovers its initial capital investment with a higher value of time. The early realization of high ETC market share entitles the toll agency to enjoy significant cost reductions, primarily toll collection staff, for a longer period.

ETC Specific Constant and Network Externalities

We suspect that the reluctance to switch to ETC will decrease over time but we are not sure how quickly. In the original model we supposed that the constant (α_0) hits zero in year 20 by decreasing at a uniform rate. In this section, different rates are investigated. Following our argument about network externalities, we believe that the magnitude of this constant is associated with the share of ETC users (or nonusers). Here we take $\alpha_0=\alpha_0 * S_m^z$, using the share of manual users (S_m) as surrogate. Different power terms (z) are tested and the results are displayed on Figure 4.

For a number of years the power term results behave in an orderly way. Up to year 12, the rankings in terms of market share are clearly proportional to the power term, with a power term of 2 resulting in the highest share and -1 in the lowest. A high power term means that positive feedback for ETC is strong (a virtuous circle), users beget more users, in the model the value of ETC specific constant becomes small. A power term of 0 implies that there are no feedback effects, while a negative power term implies positive feedbacks in the opposite direction (a vicious circle), the more ETC users the greater the value of the alternative specific constant.

However, the lower the power term (below 1), the sooner the agency will deploy all 11 lanes. That is, when it must fight against a vicious circle to maximize welfare it will go all out and make the choice of manual lanes untenable due to high travel times. But also the lower the power term, the lower the final ETC market share.

What is the real value of the power term? To ascertain this, we use the best available data for the Carqui ez Bridge. The number of transponders at the Carqui ez Bridge in year 2 is converted to get the approximate market share, 9.2% for the second year. Using 6% of market share for the first year, 84% of ETC users in first year staying in the same commuting area, a 34.6-second difference in travel time, and $0.15 discount for ETC users, we estimate the power term equal to —1.636, less than -1. The overall NPV for this scenario is negative.

Two points should be noted about this unpleasant result. First, most ETC travelers use the system during the peak period, and the choice model we use is built for estimating ETC market share during the peak period as well. However, we do not have data broken down by peak/non-peak. We expect that the market share should be higher during the peak period and the ETC specific constant should be lower than we have now. Secondly, maybe the reluctance is really that strong. That means, the toll agency has to do something to affect people s preference if it wants to proceed with ETC. Because the Carqui ez ETC system is presently considered a technology test rather than a market demonstration, very little effort has been made to sell ETC to potential customers. We presume this will change.

Alternative Capacity Rules

In the original model, the capacity is decided by optimizing overall NPV in a given year, independent of its consequences for future years. From the last two sections, a greater number of ETC lanes usually results in higher overall NPV over the entire period. Is it possible to trade a suboptimal NPV in the present year for a higher long-term NPV? The original capacity rule is dubbed myopic optimization." Clearly, the best approach to solve this problem would be to optimize the ETC allocation and price discount for all 20 years simultaneously. However, constrained by computation time, we try several heuristic alternatives. Our first heuristic, rather than necessarily starting with 1 ETC lane in year 1, is to specify higher numbers of ETC lanes in this first year, and then estimate the number of ETC lanes myopically. Our second heuristic adapts the original capacity rule by adding one and two more lanes to the myopic optimization results. In the third heuristic, dubbed bundling , instead of the idealized 20 years, we optimize the number of ETC lanes and price discount for two-year, three-year, and four-years simultaneously.

We suspect that if travelers are forced to switch to ETC payment as early as possible, overall social welfare over the 20 years should be greater. By forcing travelers to switch earlier, future benefits would be realized earlier at the expense of lower welfare in the earlier years. In this simulation, we set up the number of ETC lanes in the first year, and use the same myopic rule afterwards. The evolution of ETC share with alternative capacity rules is shown on Figure 5. Restricted by the condition that the NPV of the toll agency has to be always greater than zero, the maximum number of ETC lanes can be deployed in the year one is three. Interestingly, the saturated ETC market share converges to certain range in year 20 no matter the initial seed number of lanes. The maximum overall social welfare is gained when two ETC lanes are installed in the first year.

Another rule adds one and two more lanes to the number of ETC lanes computed from the myopic optimization rules. The results for evolution of ETC share with different capacity rules are shown on Figure 6. Again, the results confirm our early observation that the earlier additional ETC lanes are deployed, the greater the overall NPV is gained over the 20-year period.

Finally, we optimize the number of ETC lanes in two-year, three-year, and four-year bundles, where otherwise all assumptions are the same as the original model. Figures 7 depicts the results. The longer time span we take into account, the better overall results we get compared to the myopic optimization rules. A four-year optimization will be superior to the two-year optimization. The three-year bundle model is almost identical with the two-year bundle model. The gap between two-year, three-year, and four-year model is not as much as between the myopic and two-year model. We suspect that the improvements we can obtain by optimization over longer time spans is limited, and faces diminishing marginal returns.

Conclusions

The conversion of conventional toll plazas to electronic toll collection is seemingly inevitable. How quickly it occurs remains to be seen. This paper identified a process that may explain the speed of this conversion if public toll agencies strive to improve the welfare for all, but are constrained by myopia. It is clear that government policy — opening ETC lanes faster or slower - can drive user adoption of ETC. Overall welfare is improved the greater the ETC market share, and the sooner that share is achieved. Longer-term decision-making, as expected, will result in higher overall welfare than myopic decisions, though the penalty for myopia (as high as 50%) depends on other assumptions. Many of the gains can be achieved by simply looking two years out; there are diminishing returns to optimizing with an increasing number of years, while modeling costs.

This paper was intended to develop a schematic model and apply it to a particular case. As a matter of course, we have raised some questions that we are unable to answer, but which are critical when trying to strategically deploy network technologies such as ETC. In particular, we are left with the question of determining whether individuals face positive network externalities associated with the technology or whether their reluctance to make the leap is deeper. While the second year of data for the Carqui ez Bridge suggest the latter, that data is associated with little marketing as the agency attempts to ensure the technology is working smoothly. A more concerted marketing strategy to reduce the barriers to entry could easily shift preferences. Furthermore, deployment of ETC on other Bay Area bridges should also create a positive externality. Alternatively, use of Automatic Vehicle Identification, such as used on Highway 407 in Toronto, which eliminates the transponder buy-in, may be an alternative. Clearly, more empirical research is needed on user preferences for this and other new technologies, to ascertain which deployment scenario is most reasonable.

The single most important factor in the model that dictates if ETC fails or flourishes is whether the barrier to entry rises or falls over time. If additional users, or some other factors, diminish the barrier, the system will take off. If they don t, those predisposed against ETC will adopt it at a smaller and smaller increment each successive year.

Appendix: Benefits and Costs of ETC

To estimate the costs and benefits, a number of basic assumptions are made. These include overall traffic growth, toll transaction time by type of payments, travel speed, and design configuration of Carqui ez Bridge as well as the annual inflation rate and interest rate. The main assumptions are listed in Table A1 and explained below.

We apply a framework that identifies benefit and cost categories for Travelers (Time, Vehicle Operating Costs), Agencies (Fixed & Operating Costs of Toll Collection, Revenue), and the Community (Pollution). While our measure of overall net present value (NPV) ignores transfers, they are considered for the NPV of each user class. Transfers include tolls paid (a transfer from the user to the toll agency), or interest on prepaid ETC credit accounts (lost to travelers but accrued to the agency)

Costs and benefits for each class (travelers, the toll agency, and the community) can be estimated separately. The overall social welfare (W) is defined as:

$$W = B_T - C_T + B_A - C_A + B_C - C_C \tag{A1}$$

Where:

B_A, B_C, B_T benefits for the toll agency, the community, and travelers

C_A, C_C, C_T costs for the toll agency, the community, and travelers

Travelers

Travelers are divided into two classes, referred to by the shorthand manual and electronic. Cost savings for electronic travelers come from reduced delay because of higher throughputs on ETC lanes, and elimination of acceleration and deceleration processes associated with manual toll collections. For the convenience of analysis, it is assumed that the value of time, the mode split (car, truck, bus), and the average vehicle occupancy do not vary over the analysis period.

In general, delay can be decomposed into three categories: random (or overflow) delay, stop delay, and delay due to acceleration/deceleration. The random delay stands for the stochastic nature of the arrival traffic streams and manual toll collection times. When the number of arriving vehicles exceeds service capacity temporarily during some period, they must wait to pay the toll. We employ the generalized delay model suggested by Fambro and Rouphail (1997) for the new Highway Capacity Manual to estimate delay. Furthermore, we assume Poisson arrival and exponential service time (Li Rouphail and Ak Helik 1985; Lin and Su 1994; Al-Deek, Radwan, Mohammed and Klodzinski 1996; Robinson and Van Aerde 1995; Woo and Hoel 1991). The model is solved separately for manual and electronic lanes.

$$D_R = 900T_{peak}\left[(\rho-1)+\sqrt{(\rho-1)^2+\frac{8\rho}{Tm\mu}}\right] \tag{A2}$$

Where:

D_R average random delay (sec)

T_{peak} duration of peak period (hrs)

μ capacity of one lane (veh/hr)

m number of lanes

λ total arrival rate during the peak period (veh/hr) ρ degree of saturation, $\rho = \dfrac{\lambda}{m\mu}$

The stop delay is the time required by a manual user to pay the toll. For manual lanes, mean transaction time is the weighted transaction time by payment type split. The service capacity is then the inverse of the mean transaction time. For ETC lanes, transaction time is assumed to be 0 seconds, and the capacity is determined by the minimum headway, 2.4 seconds (1500 vehicles per hour) in the Carqui ez Bridge case (which retrofits ETC lanes to an older toll plaza design).

In order to make a complete stop at the toll plaza, a manual user has acceleration/deceleration delay. The distance traveled during this process is the length of ramps from and leading to the toll plaza. Drivers are assumed to accelerate and decelerate at a constant rate, and thus the average travel speed is equal to one half of the normal travel speed. The acceleration delay is estimated by dividing the length of the ramp leading to the toll plaza by this average travel speed. The same estimate is applied to the deceleration process. Electronic users escape both stop delay and acceleration-deceleration delay.

ETC users also benefit from the reduction in vehicle operating costs, mainly in fuel consumption. In general, engines need more fuel during acceleration than other times. Thus, only fuel consumption during acceleration is considered. Fuel costs are estimated as follows:

$$C_{GTn} = T_{plaza,n} \cdot G_a \cdot C_G \cdot (1 + I_f)^n \qquad \text{(A3)}$$

Where

C_{GTn} total gasoline costs in year n (dollars)

G_a gasoline consumption during acceleration (gal/hr)

I_f annual inflation rate

$T_{plaza,n}$ time needed to travel the length of toll plaza ramps in year n, (hr/yr)

C_G cost of gasoline in base year (excluding taxes) (dollars/gal)

It is expected that all ticket users will switch to ETC gradually over the 20 years. Furthermore, fuel usage is assumed independent of vehicle type. To estimate the future peak hour volume, we calculate the base year ratio of AADT (average annual daily traffic) to PHV (peak hour volume) through the toll plaza and assume that the ratio stays constant over time. During the evening peak hour, this ratio is 0.0995, and during the morning peak hour it is 0.0277 for the Carqui ez Bridge. (The tollbooth is located on eastbound I-80, which is outbound from San Francisco and Oakland).

Agency

The agency has both one-time and continuing operating costs. One-time costs are expended to establish new systems, while operating costs are incurred daily to operate the system. Among the one-time costs, some are spent at the beginning of the project, and are independent of the number of lanes open and level of traffic. The costs of installing additional ETC lanes and purchasing transponders are allocated to the year associated with the incremental increase in ETC users.

The operating costs can be divided into three categories: staffing, hardware/software, and other. Staffing is comprised of employees in information technology, accounting, and toll collection. Personnel costs for information technology (P_I) and accounting (P_A) are assumed constant over time (Caltrans 1995). Only toll collection personnel (P_{Tn}) vary with traffic volume, so those are estimated by the model. A promising cost savings for the toll agency from adopting the ETC alternative is the reduction in toll collection staff, proportionate to the number of manual lanes. Staff costs are estimated by multiplying the personnel needed for each alternative and the cost per person. The number of persons needed for toll collection can be estimated given forecast annual traffic volume and ETC market share. The costs of staffing can be obtained as follows.

$$C_{PTn} = C_P \cdot (P_A + P_I + P_{T_n}) \cdot (1 + I_f)^n \tag{A4}$$

Where:

C_{PTn}	total personnel cost in year n (dollars)
C_P	person year costs in base year (dollars/yr)
P_A, P_I, P_{Tn}	person years for accounting. information, toll collection in year n

We ensure that the toll collection staff is balanced with the traffic level in the base year. Furthermore, we assume that all manual lanes are open during the peak hour, and the personnel needed during the off-peak period is proportional to the number of manual transactions during the off-peak. Off-peak traffic is estimated by subtracting projected annual peak traffic from the projected annual traffic volume. In our model, we assume the ETC share is the same during the peak and off-peak period. However, it might be more realistic to expect that the ETC share will be higher during the peak hours when significant time may be saved, and because peak travelers are more regular users of the system. Hardware/software costs for information technology and other program costs are estimated from the ATCAS Report (Caltrans 1995).

Community

The primary benefit of ETC systems to communities at large is the reduction of NOx, HC, and CO emission during idling and acceleration. Total emissions of pollutant p from idling in year n ($E_{idleT,p,n}$), (in gm) are estimated as follows.

$$E_{idleT,p,n} = T_{idle,n} \cdot E_{idle,p} \cdot 60 \tag{A5}$$

Where:

$T_{idle,n}$	time idling in year n (hr)
$E_{idle,p}$	emission rate for pollutant type p during idling (gm/min)

Total emissions of pollutant p from acceleration in year n ($E_{accT,p,n}$) (in gm) are:

$$E_{accT,p,n} = (T_{plaza,n}) \cdot G_a \cdot E_{acc,p} \tag{A6}$$

Where:

$E_{acc,p}$ emission rate of pollutant type p during acceleration (gm/gal)

G_a fuel consumption rate during acceleration (gal/hr)

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Figure 1: Flowchart of the Basic ETC Optimization Model

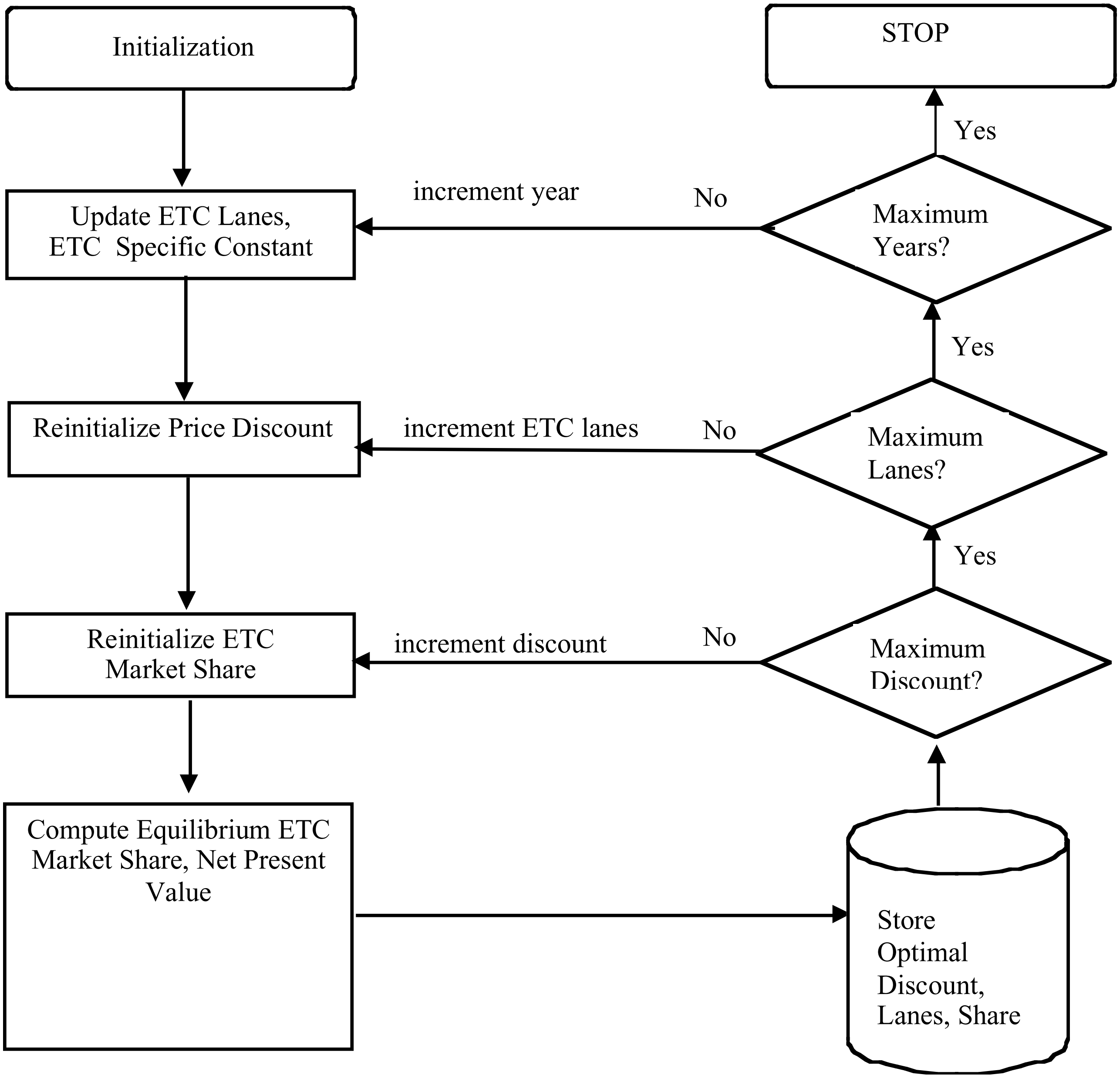

Figure 2: Evolution of ETC Market Share under Different Survival Rate

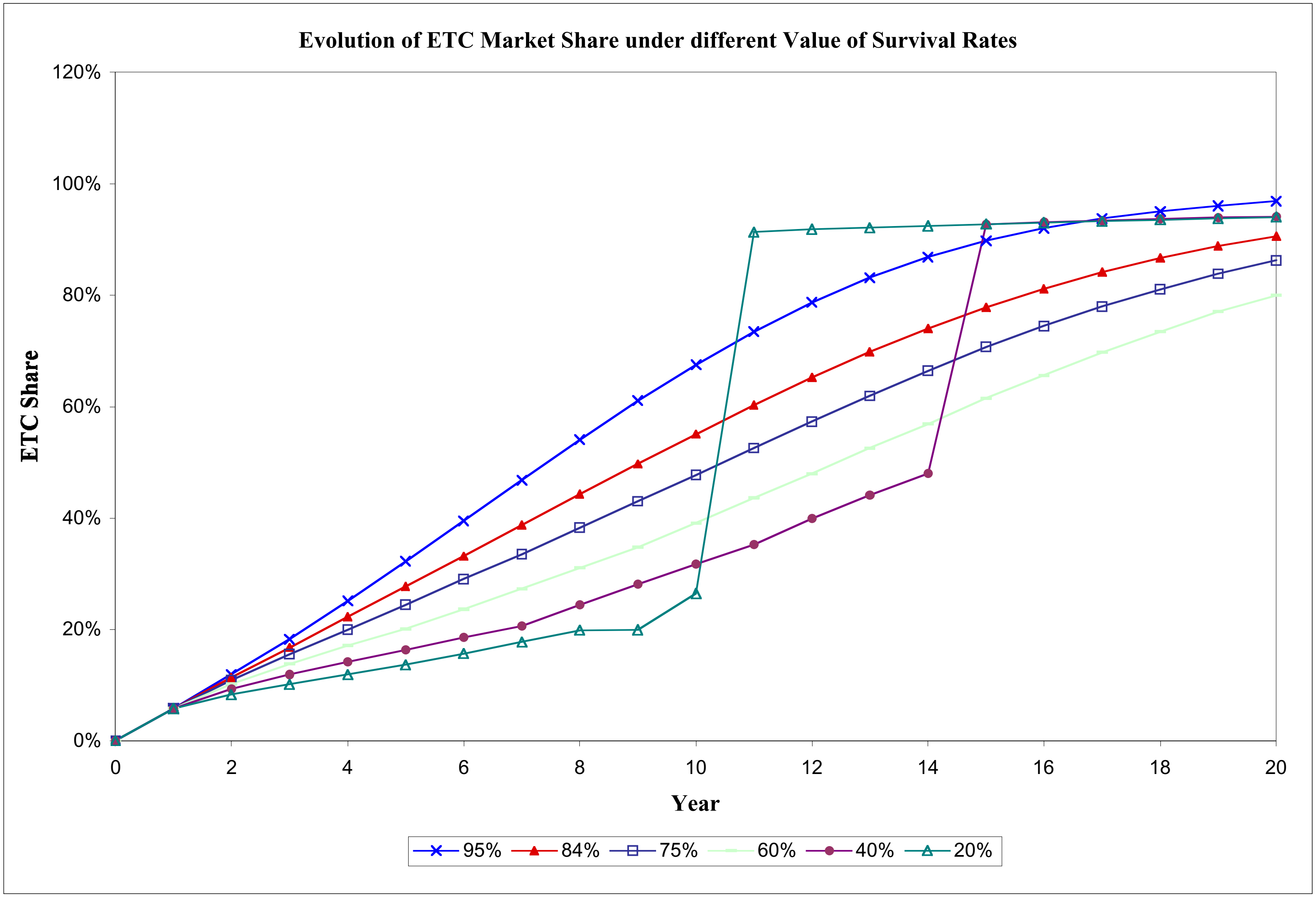

Figure 3: Evolution of ETC Market Share under Different Value of Time

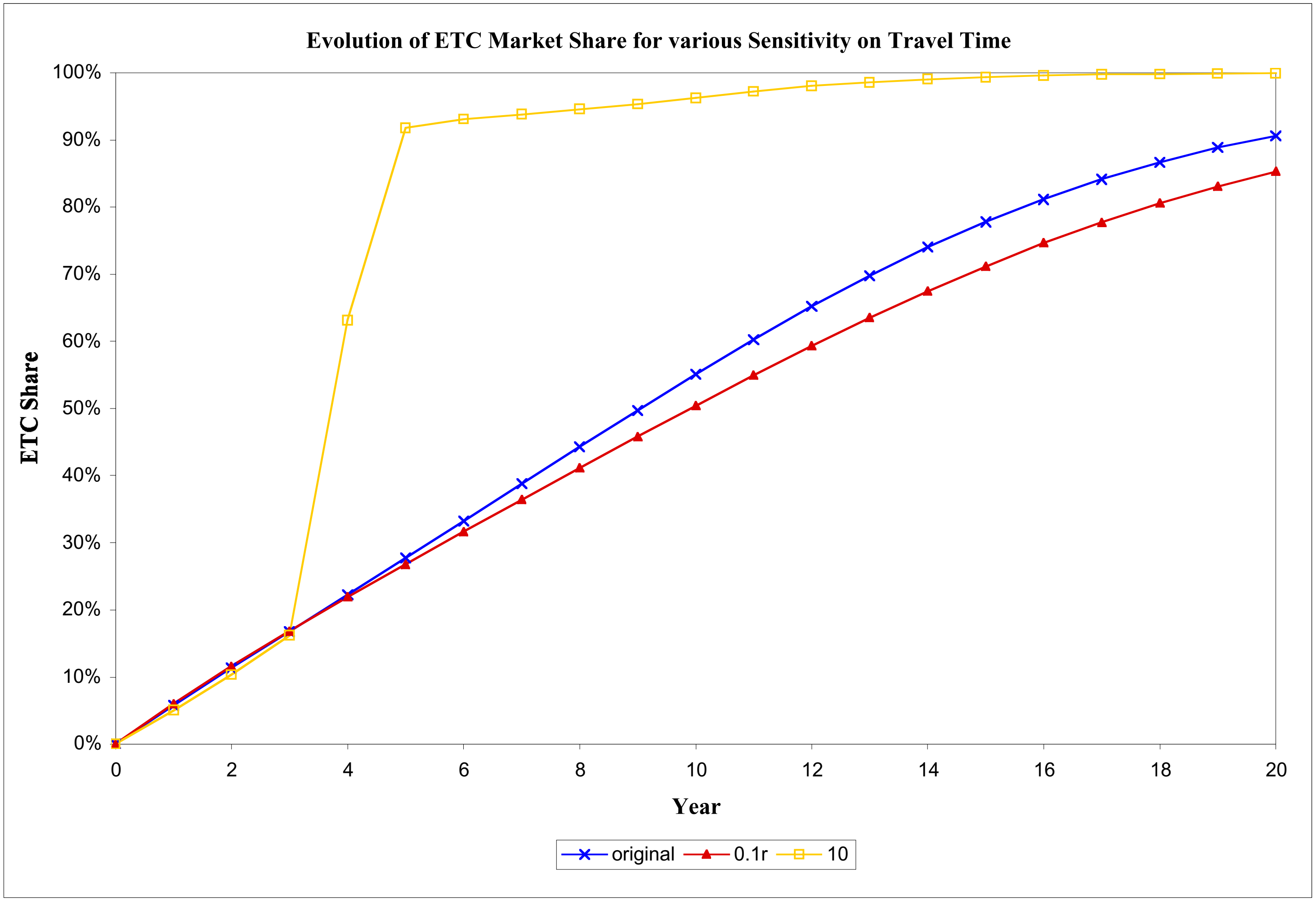

Figure 4: Evolution of ETC Market Share under Different Power Terms

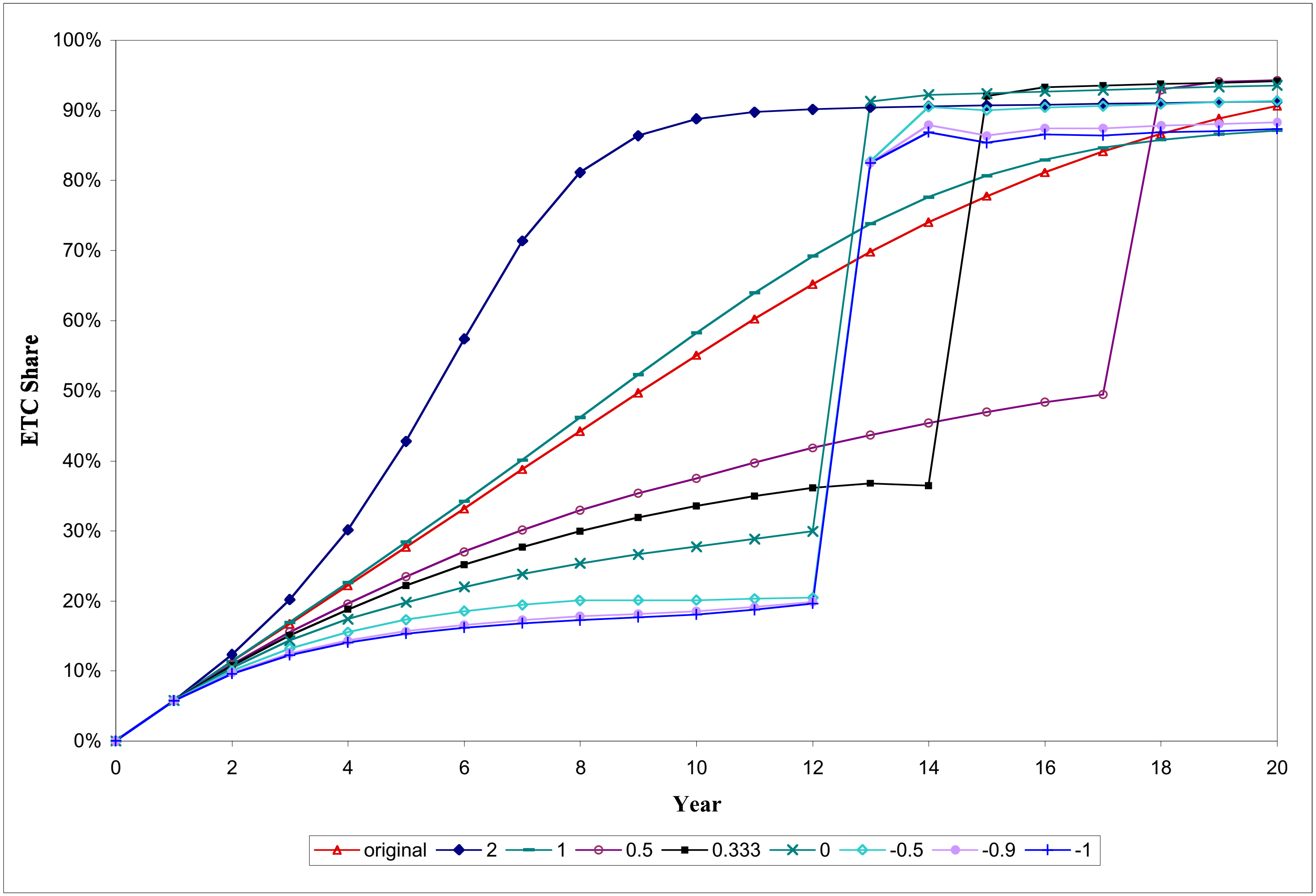

Figure 5: Evolution of ETC Share under Alternative Capacity Rule: Number of ETC Lanes in the First Year

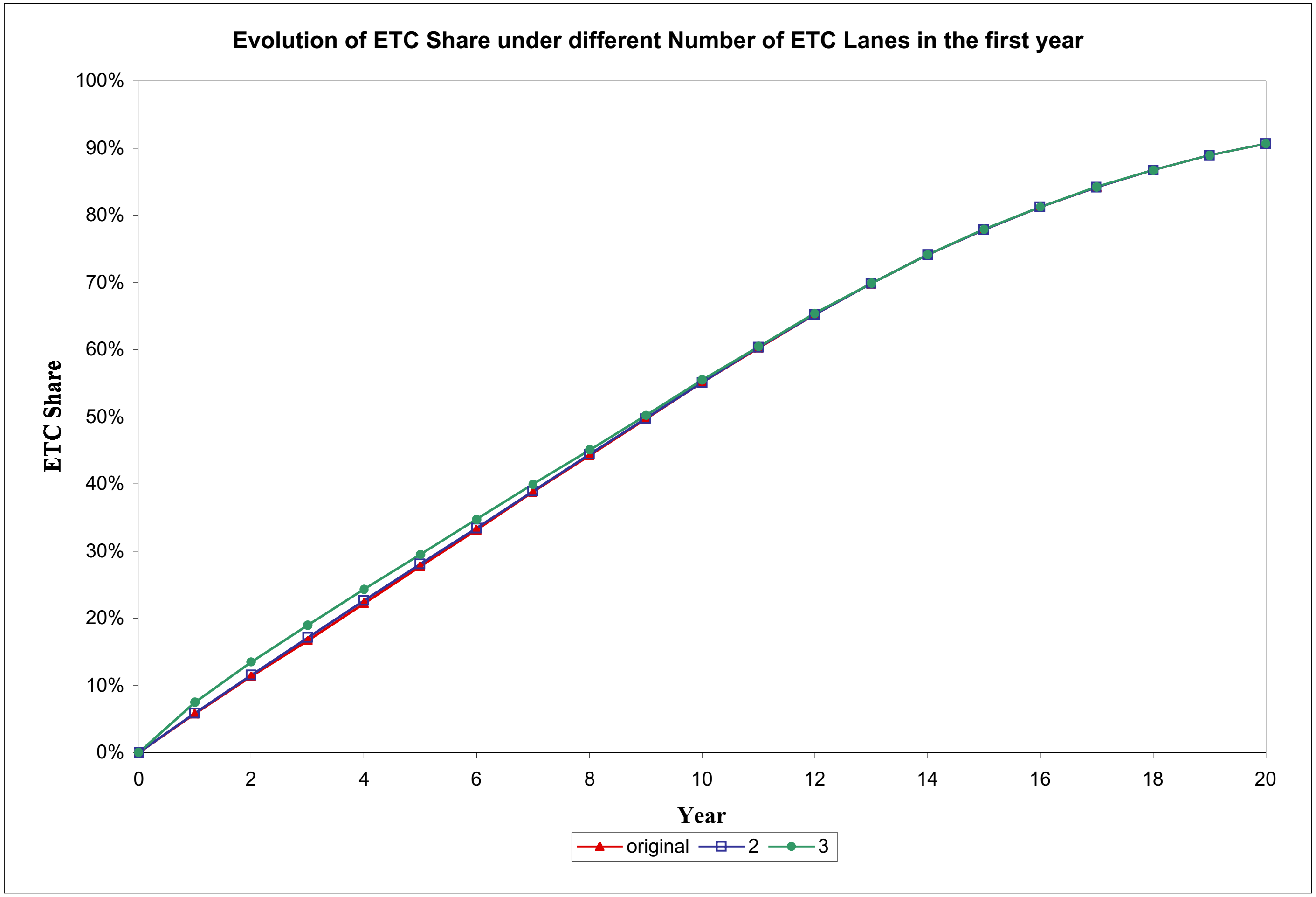

Figure 6: Evolution of ETC Share for Different Capacity Rules

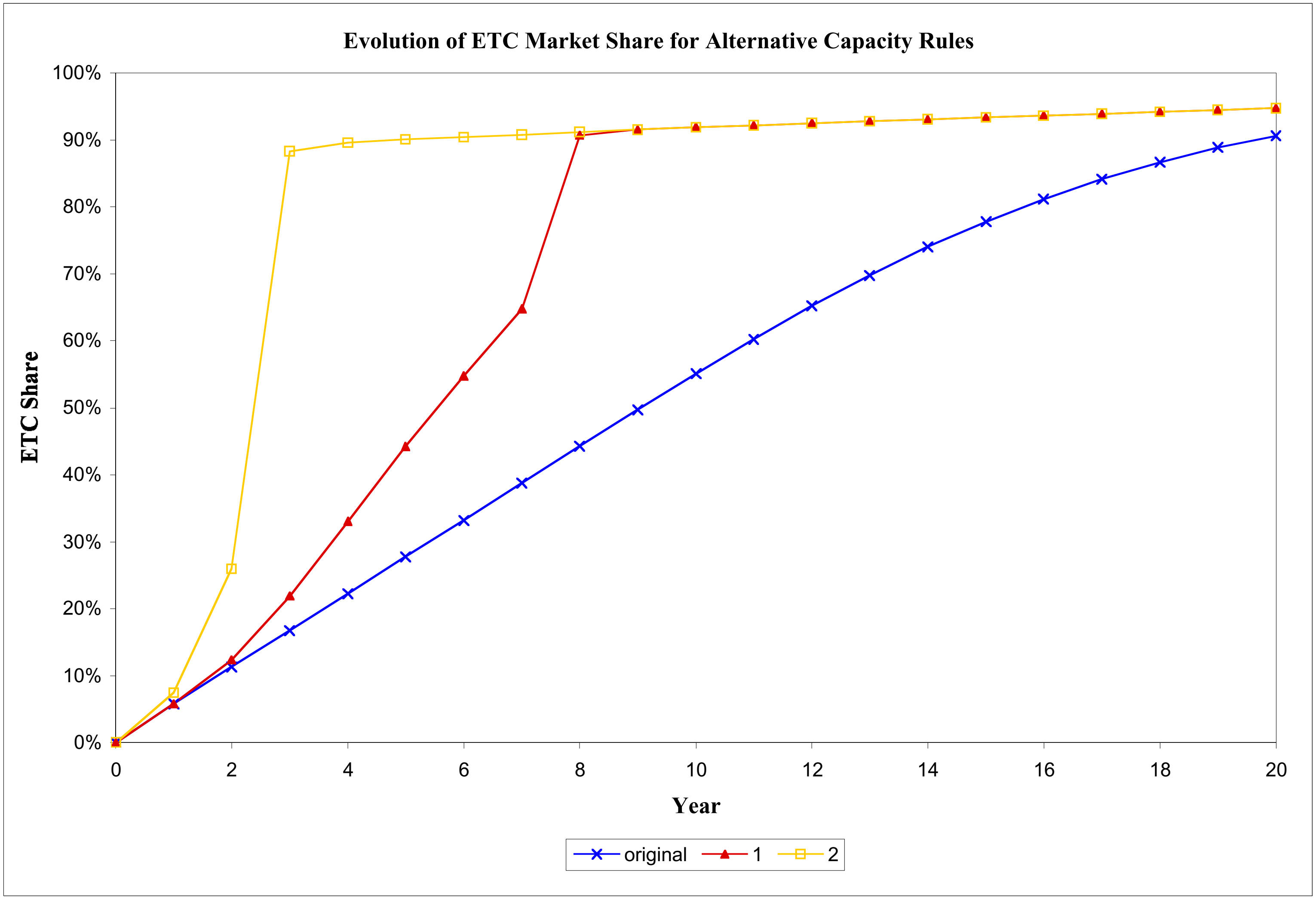

Figure 7: Evolution of ETC Share under Different Optimization Rules

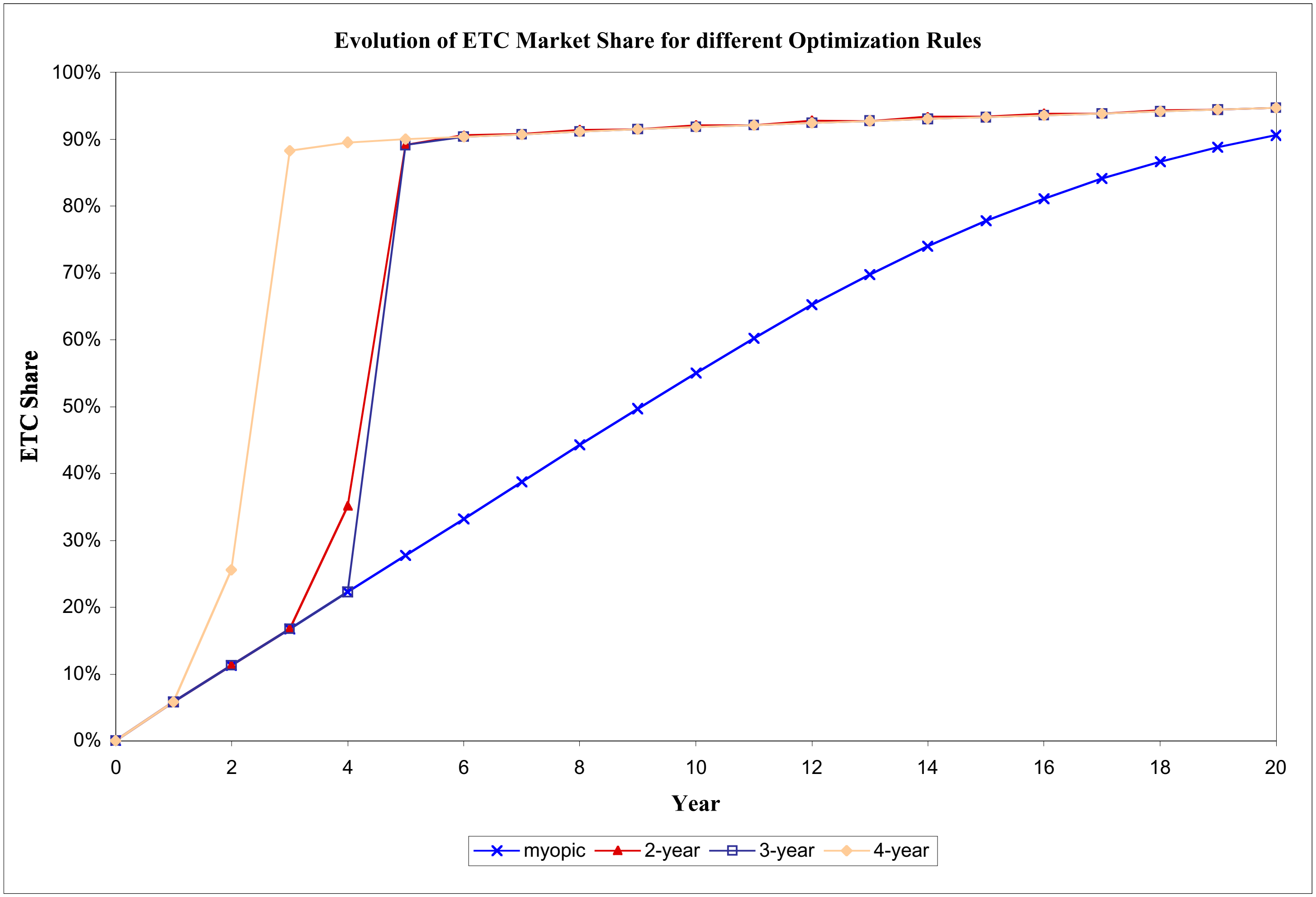

Table 1: Summary of Results

	Overall NPV	Agency	Users	Society	Max. Lanes	Saturation ETC share
Baseline						
	$73,835,899	-$1,586,679	$75,360,179	$62,400	8	86.82%
Survival Rate						
95%	$81,832,093	-$1,417,912	$83,180,926	$69,080	10	95.47%
75%	$68,311,591	-$1,708,067	$69,961,850	$57,808	7	80.84%
60%	$60,715,884	-$1,550,326	$62,214,736	$51,474	6	72.53%
40%	$52,878,116	-$1,615,916	$54,449,127	$44,905	5	63.87%
20%	$46,540,082	-$1,785,871	$48,286,206	$39,747	4	57.13%
Value of Time						
$174	$401,875,521	$3,098,232	$398,705,738	$71,551	11	94.51%
$1.74	$43,993,659	-$1,300,174	$45,231,678	$62,155	9	86.64%
Power Term						
2	$75,503,504	-$1,494,009	$76,933,426	$64,087	8	86.20%
1	$53,754,348	-$1,573,507	$55,282,089	$45,766	6	74.67%
0.5	$24,514,291	$1,042,714	$23,445,267	$26,310	3	46.35%
0.33	$10,460,399	-$1,819,623	$12,261,059	$18,963	3	39.64%
0.25	$6,299,887	-$1,871,985	$8,155,251	$16,620	3	38.47%
0.125	-$771,101	-$1,838,256	$1,054,487	$12,668	2	34.76%
0	-$9,090,115	-$1,897,567	-$7,200,851	$8,302	2	33.45%
-1	-$32,403,453	$1,825,355	-$34,223,128	-$5,680	1	19.49%
Capacity Rules						
+1 year 1	$68,311,591	-$1,708,067	$69,961,850	$57,808	7	80.84%
+1 year 2	$52,878,116	-$1,615,916	$54,449,127	$44,905	5	63.87%
+2 year 1	$60,715,884	-$1,550,326	$62,214,736	$51,474	6	72.53%
+2 year 2	$46,540,082	-$1,785,871	$48,286,206	$39,747	4	57.13%
Optimization Bundling						
2 - Year	$95,084,413	-$4,815,726	$99,816,884	$83,254	10	88.43%
3 - Year	$83,386,893	-$4,563,586	$87,871,877	$78,602	11	92.63%

Table 2: Detailed Results for Baseline Scenario

Year	ETC Share	Overall NPV	Discount	Time Difference (min)	ETC Lanes
0	0.00%	-$2,223,592			
1	5.98%	$253,415	-$0.11	-0.59	1
2	11.54%	$531,627	-$0.13	-0.56	1
3	17.69%	$854,635	-$0.14	-0.50	1
4	25.41%	$1,215,254	-$0.14	-0.57	2
5	35.25%	$1,737,885	-$0.15	-0.53	2
6	46.89%	$2,326,685	-$0.16	-0.55	3
7	58.74%	$3,044,073	-$0.17	-0.55	4
8	68.92%	$3,751,064	-$0.20	-0.56	5
9	76.32%	$4,348,375	-$0.22	-0.54	5
10	81.06%	$4,747,283	-$0.24	-0.55	6
11	83.81%	$5,034,428	-$0.25	-0.55	6
12	85.30%	$5,181,423	-$0.27	-0.56	7
13	86.07%	$5,292,668	-$0.28	-0.56	7
14	86.45%	$5,334,956	-$0.29	-0.56	7
15	86.63%	$5,357,705	-$0.30	-0.58	8
16	86.72%	$5,396,055	-$0.31	-0.58	8
17	86.76%	$5,403,914	-$0.32	-0.58	8
18	86.79%	$5,410,090	-$0.33	-0.58	8
19	86.81%	$5,415,931	-$0.34	-0.58	8
20	86.82%	$5,422,026	-$0.35	-0.59	8
Total		$73,835,899			

Table A1 Assumptions

Items	Value		
General Assumptions			
Annual traffic growth rate	3%		
Seconds/cash transaction	7.5		
Seconds/ticket transaction	4.5		
Seconds/ETC transaction	2.4		
Normal travel speed (mph)	55		
Ramp distance to toll plaza (mile)	0.2		
Annual discount rate	6%		
Annual inflation rate	3%		
Average miles/gallon	25		
Pre-tax fuel price (excluding taxes) ($/gal)	$0.74		
Modal Use Assumptions			
	Auto	Truck	Bus
Mode split	94.76%	5.11%	0.13%
Average vehicle occupancy	1.258	1.1	20
Value of time per passenger	$12.75	$33.41	$12.75
Agency Assumptions			
Costs per personal year ($/PY)	$65,000		
Unit cost of ETC lanes	$62,361		
Unit cost of transponders	$28.85		
Person Years needed for information technology	0.11		
Person Years needed for accounting	0.46		
Average number of transponders per ETC account	1.35		
Average annual times an account is used	160		
Community Assumptions			
	NOx	HC	CO
Emission rate during the acceleration (grams/gallon)	24.7	9.5	209.0
Emission rate during the idling (grams/minute)	0	0.15	2.5
Cost of Air Pollution ($/kg of pollutant)	$1.275	$1.275	$0.0063
Payment Split Assumptions			
Payment Split	Cash	Ticket (Credit Card)	
Baseline	83% in base year; 83% in year 20	17% in base year; 17% in year 20	
ETC alternative-Manual users	83% in base year; 100% in year 20	17% in base year; 0% in year 20	
ETC alternative-ETC users	64% in base year; 64% in year 20	(36% in base year; 36% in year 20)	

Source: ATCAS Feasibility Report (1995) Li et al (1995) pp.13, 21, 22, A-13, Table B-1,B-2, C-2

Table A2 Summary of Variables

Variable	Description
B_A, B_C, B_T	benefits for the toll agency, the community, and travelers
C_A, C_C, C_T	costs for the toll agency, the community, and travelers
C_G	gasoline cost in base year (dollars/gal)
C_{GTn}	total gasoline costs in year n (dollars)
C_P	person year cost in base year (dollars/yr)
C_{PTn}	total personnel cost in year n (dollars)
D_R	average random delay (sec)
$E_{acc,p}$ $E_{idle, p}$	emissions of pollutant p during acceleration (gm/gal), idling (gm/min)
$E_{accT,p,n}$ $E_{idleT,p,n}$	total emissions of pollutant p from acceleration, idling in year n (gm)
G_a	gasoline consumption during acceleration (gal/hr)
I_f	annual inflation rate
m	number of lanes
M_e, M_m	toll in electronic, manual lane (dollars/veh)
P_A, P_I, P_{Tn}	person years for accounting, information, collection in year n
$S_{e,n}$ $S_{m,n}$	share of electronic, manual toll collection users, in year n
S_R	survival rate of commutes
T_e T_m	travel time in electronic, manual toll collection lane (min)
$T_{idle,n}$	time idling in year n (hr)
T_{peak}	duration of peak period (hr)
$T_{plaza,n}$	time to travel the length of toll plaza ramps in year n, (hr/yr)
U_e, U_m	utility of electronic, manual tolls
V_T	value of time (dollars/hr)
W	overall social welfare
α_0, α_1, α_2	choice model parameters
λ	total arrival rate during the peak period (veh/hr)
μ	capacity of one lane (veh/hr)
ρ	degree of saturation, $\rho = \frac{\lambda}{m\mu}$