Using Microsimulation to Quantify the Impact of Electronic Toll Collection

BY MARK W. BURRIS AND ERIC D. HILDEBRAND

The Halifax-Dartmouth Bridge Commission in Nova Scotia, Canada, is examining the replacement of automatic coin machines on its bridges as age (25 years old) makes them increasingly difficult to maintain. One option available is the incorporation of electronic toll collection (ETC) into the current toll collection methods. Vehicles using ETC can pass through toll booths at highway speed while tolls are paid electronically. This could substantially reduce time delays, vehicle emissions, fuel consumption, vehicle operating costs and the toll authorities, operating costs. These savings are heavily dependent upon the percentage of users choosing to use ETC, current congestion levels, and existing traffic capacity up- and downstream of the toll plaza.

These factors, along with several less critical variables (such as performance of current equipment) make ETC’s net effect on traffic uncertain. Therefore, it was important to examine the potential effect of ETC before the bridge commission proceeded with its implementation.

Microsimulation Modeling

A discrete-event, stochastic, microsimulation computer model was built to determine the impact of ETC on traffic operations. Simulation modeling was used so that the many intricacies of toll collection at the bridge could be accommodated. Models were developed that examined all aspects of the toll collection process, including vehicle deceleration, queuing, lane selection logistics, service time and vehicle acceleration. Simulation modeling allowed the inclusion of different vehicle types, payment methods and lane usage under a variety of toll plaza configurations. Data generated by the model simulation runs could then be used to analyze the effect of ETC more accurately than with conventional queuing analysis. The option of using animation to visualize the effects of ETC was also available with a link to animation.

Model Creation

At the onset, a base model was created to replicate existing conditions on the A. Murray MacKay Bridge in Halifax, including toll collection methods and traffic volumes. To construct this model, a great deal of empirical data were required, particularly traffic data including hourly, daily, monthly and yearly traffic volumes, service time distributions, percentage of vehicles using each payment option, lane usage, vehicle types, lane changing patterns and so on.

To simplify model development, inbound and outbound traffic were simulated separately. Each model first generated created vehicles some distance prior to the toll plaza. The generation rate followed a (negative) exponential distribution pattern, representative of a random arrival pattern. Once generated, the vehicles were assigned a type (passenger vehicle or bus/truck) according to their proportion in the existing traffic stream. Vehicles also were categorized on the basis of payment method.

Each vehicle would attempt to enter a toll booth queue. If all toll booth approach lanes were full, the vehicle waited until a space became available. Vehicle selection of the toll booth lane was developed through a logistical routine based on queue lengths, traffic volumes, payment preference and proximity to appropriate booths. Once in a toll booth queue, vehicles advanced to the toll booth, entered when it became free,

Mark W. Burris is a Research Associate at the Center for Urban Transportation Research in Tampa, Fla. He holds a B.Sc.E. in civil engineering and an M.Sc.E. in transportation engineering, and is pursuing a Ph.D. at the University of South Florida. Burris is a Member of ITE.

Eric D. Hildebrand is an Assistant Professor in civil engineering at the University of New Brunswick, Canada. He has a B.Sc.E. in civil engineering and an M.Sc.E. in transportation and planning, and is currently working toward a Ph.D. at the University of Waterloo.
Table 1. Toll plaza scenarios modelled

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Toll Plaza Configuration (number of lanes open in each direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Base Case)</td>
<td>3 ACM lanes and 2 ACM/Manual lanes</td>
</tr>
<tr>
<td>2</td>
<td>4 ACM lanes and 2 ACM/Manual lanes</td>
</tr>
<tr>
<td>3</td>
<td>3 ACM/ETC lanes and 2 ACM/ETC/Manual lanes - medium ETC participation rate</td>
</tr>
<tr>
<td>4</td>
<td>3 ACM/ETC lanes and 2 ACM/ETC/Manual lanes - low ETC participation rate</td>
</tr>
<tr>
<td>5</td>
<td>3 ACM/ETC lanes and 2 ACM/ETC/Manual lanes - high ETC participation rate</td>
</tr>
<tr>
<td>6</td>
<td>2 ACM lanes, 1 ACM/ETC lane, 1 ACM/Manual lane and 1 ACM/Manual/ETC lane - medium ETC participation rate</td>
</tr>
<tr>
<td>7</td>
<td>2 ACM lanes, 1 ETC lane, 1 ACM/Manual lane and 1 ACM/Manual/ETC lane - medium ETC participation rate</td>
</tr>
<tr>
<td>8</td>
<td>3 ACM lanes, 1 ETC lane, 1 ACM/Manual lane and 1 ACM/Manual/ETC lane - medium ETC participation rate</td>
</tr>
</tbody>
</table>

ACM = automatic coin machine

were serviced, and then advanced to a model cordon where they exited simulation. Each vehicle was tracked from generation to termination, and statistics such as time and speed were recorded throughout the vehicle’s progression.

Model Verification

Model verification is the process of examining the conceptual aspects of the model to ensure it works logically. For this model, two verification processes were employed. First, vehicles were tracked through the entire model as they moved from creation to termination, to ensure they moved through the model in a logical sequence. Second, different vehicle flow rates were modeled, and the resulting traffic patterns and lane usages were compared to hourly data collected by the bridge commission. Several flaws in the model logic were found and corrected through these procedures.

Model Validation

To further ensure that the computer model accurately simulates the actual system, a more rigorous statistical comparison was performed. To validate each model, two variables were examined: the length of time vehicles spend in the system and the number of vehicles in the queues. Data were collected for vehicle time in the system and average number of vehicles in the queues for several different traffic densities from both the model and the real-world system.

A heuristic comparison of the cumulative frequency distributions of the two data sets showed the model to be highly accurate, with one exception. The outbound model overestimated the number of vehicles in the system during periods of high flow rates, but only twice did the model miscalculate by more than 5 percent.

The second method used to validate the model was a comparison of the model and real system data means. This was accomplished by a two-sample t-test performed on the data. This test measures how well the two-sample means compare, with higher values indicating a better correlation. The results clearly showed a strong relationship between the model data and real data. The mean values derived from the model were all within 4 percent of the real system mean values, except in the outbound model when attempting to predict the number of vehicles in the system during high traffic volumes. With these tests, the model was shown to be statistically representative of the real system, in both data distribution and data mean under different traffic densities. The model was particularly accurate in predicting the most critical variable: vehicle time in the system.

Model Application

The base case models were then modified to include two additional toll booths (currently used as spares), one in each direction, for use during periods of peak demand (Scenario 2). This scenario was examined to determine to what extent the current toll collection process could be improved without adding ETC. Table 1 outlines the eight scenarios examined.

The addition of ETC dedicated and shared lanes was modeled in various configurations, and data on the resulting traffic flows were recorded. Many other scenarios are possible, but various factors make their application improbable. To accurately reflect the end use of ETC in the model, an extensive literature review of that topic was undertaken. From this review it was concluded that the most appropriate ETC technology for use on the Halifax–Dartmouth bridges would be a radio-frequency identification (RFID) system. The model therefore assumed this type of toll collection equipment when modeling service times and speeds for ETC-equipped vehicles.

To further incorporate ETC in the model, additional disaggregation of vehicle types was required to include ETC-capable trucks and passenger vehicles. Toll payment service times for these new vehicle types were estimated using basic speed/distance/time calculations. Since ETC-equipped vehicles are not required to stop, service times are simply the time required to drive through the plaza.

It was also necessary to estimate ETC participation rates. The ideal method to forecast the percentage of travelers who would switch to electronic payment is a market survey. Unfortunately, a survey of bridge users was not possible. Instead a review of the literature on North American ETC-equipped toll plazas provided an estimate of the percentage of bridge patrons who would be expected to switch to ETC. The literature indicated a wide range of participation rates, but the majority were between 20 percent and 40 percent for passenger vehicles and slightly higher for commercial trucks. The percentage of ETC users in the traffic stream gener-
ally increases during the peak traffic hours, given the higher proportion of daily commuters who tend to use ETC more than the general population. Based on experiences elsewhere, various conservative levels of ETC user participation rates for the MacRay Bridge were tested.

The speed that ETC-equipped vehicles can approach and exit the toll plaza is another important variable to accurately model. This speed will dictate the total time savings derived from ETC use. The bridge commission is expecting to impose a maximum speed limit of 30 mph for ETC users. Using spot speed data collected at the toll plaza, typical approach and exit speeds of current users were obtained. From this data, approach and exit speeds were estimated for ETC vehicles. Time savings for ETC vehicles over non-ETC vehicles were determined from the difference in speeds.

All eight scenarios were simulated numerous times, using different random number streams, to compensate for the inherent randomness of the model.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Avg. Time in System (sec/veh)</th>
<th># Vehicles in the System</th>
<th>ETC Vehicles*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Base Case)</td>
<td>26.2</td>
<td>13.2</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>21.9</td>
<td>9.5</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>18.1</td>
<td>7.9</td>
<td>2,494</td>
</tr>
<tr>
<td>4</td>
<td>19.4</td>
<td>8.6</td>
<td>1,461</td>
</tr>
<tr>
<td>5</td>
<td>16.9</td>
<td>7.4</td>
<td>3,529</td>
</tr>
<tr>
<td>6</td>
<td>18.1</td>
<td>7.9</td>
<td>2,005</td>
</tr>
<tr>
<td>7</td>
<td>19.0</td>
<td>8.6</td>
<td>3,814</td>
</tr>
<tr>
<td>8</td>
<td>17.5</td>
<td>7.6</td>
<td>3,851</td>
</tr>
</tbody>
</table>

* = the number of ETC-equipped vehicles able to travel through the plaza at 30 kph

Results from each model were derived from 50 independent runs, each representing a full day of traffic volume. Aggregate traffic data results of each scenario are depicted in Table 2. These results were aggregated and factored, accounting for variations in traffic on work and nonwork days, to represent average values for a typical vehicle during 1996. Data in this table can be used to determine the time savings achieved by vehicles in the various scenarios over the base case. For example, the average time a vehicle spends in the system under Scenario 2 is 4.3 seconds less than in the base case.

The average vehicle time in the system and average queue length were then

---

**Where are your high accident locations?**

[Image of a map showing accident locations]

**Intersection Magic® Software can tell you that, plus:**

- Customized collision diagrams
- Charts on Time of Day, DUI, Type of collision, etc. Any user criteria!
- Frequency reports, accident lists, custom reports, etc.
- GIS compatible output
- MS Windows® compatible

Used by over 100 cities in 20 states!

For information, contact PD Programming, Inc., or ask your consulting engineer about Intersection Magic®.

Questions may also be directed to Hartzog & Crabill Inc. These Los Angeles area consulting traffic engineers have teamed up with PD Programming, Inc. Working together, we can help you with all your engineering needs. (714) 731-9455

PD Programming, Inc. • (303) 666-7896 • 1235 Apollo Drive • Lafayette, CO 80026 • fax 666-7347 • info@pdprog.com
calculated for each scenario during the rush hour periods alone (7 to 8 a.m. and 4 to 5 p.m.). The results indicate a large decrease in both average vehicle times (up to 64 seconds) and queue lengths (up to 55 vehicles) during the rush hours.

Discussion of Model Run Results

The opening of an extra ACM lane in each direction (Scenario 2) greatly reduced average times and queue lengths over the base case. Not surprisingly, the addition of ETC further reduced the average vehicle time in the system and average queue length, although these gains were relatively modest compared to that of opening the extra lane in each direction.

Comparing Scenarios 3, 4 and 5 illustrates the effect of ETC participation rate on the overall benefits of installing ETC. A 10 percent increase in participation rate affected the critical variables as follows:

- Decreased average time in the system by 1.2 seconds (5 percent)
- Decreased average queue length by 0.6 vehicles (5 percent)
- Increased the number of vehicles that flow through the booth at 30 mph by 1,030

These results cannot necessarily be applied to all ETC participation rates and all toll plaza configuration scenarios. Nevertheless, the trend is clear—the greater the ETC participation rate, the greater the benefits derived from ETC.

Results from Scenarios 6 (four shared ETC lanes) and 7 (two shared and two dedicated ETC lanes) were used to determine what benefits, if any, could be derived from dedicated ETC lanes. In this instance, the use of dedicated lanes proved ineffective and actually increased the average vehicle time in the system by 0.85 seconds (see Table 1). Thus, without opening any extra lanes, Scenario 6 offers the lowest average vehicle time in the system. Scenario 8 offers even lower average times in the system, but two additional lanes must be opened.

Model output generated for peak hour traffic indicated that most benefits (including more than 80 percent of vehicle travel time savings) gained through reconfiguration of the plaza are realized during these congested periods. During off-peak hours, the toll plaza generally runs smoothly; therefore little is gained with plaza reconfiguration.

Finally, the most obvious result was that any scenario examined is clearly better than the base case. If ETC was not installed and Lanes 7 and 8 were simply opened, a 16.7 percent drop in average vehicle time in the system could be achieved over the course of the day. Under the least-effective ETC scenario (Scenario 4, low participation rate) there was still a decrease of 26.1 percent in the average vehicle time in the system.

Cost-Benefit Analysis of the Model Output

The potential costs and benefits associated with each toll plaza configuration were examined, including:

- Purchase price of the ACM and ETC equipment.
- Operation and maintenance costs for ACM, ETC, manned lanes and combinations of these lane types.
- Purchase price of ACM and ETC plaza computers and operating software.
- Purchase price of RFID vehicle tags.
- Vehicle operating costs associated with ETC, ACM or manual toll payment.
- Marketing and advertising associated with ETC.
- The value of the time savings achieved by users under the various scenarios.

The capital, operating, maintenance and vehicle tag costs used in this study were based on industry standards. In addition, there is still substantial debate over the exact cost associated with a unit of vehicle emissions. There is also disagreement over whether a small amount of travel time saved (for instance, 5 seconds) has any real value. Given these uncertainties, the estimates used in this study are simply medians in a range of possible values. The most significant component contributing to costs and benefits is the value of travel time savings. These values outweigh most other factors by tenfold.

Conclusions

Following the completion of this study, a number of conclusions were derived.

1. Once a microsimulation model was developed and calibrated to represent the MacKay Bridge toll plaza, it provided an excellent tool to test the effect that different toll collection scenarios will have on all aspects of traffic operations.

2. The Halifax–Dartmouth Bridge Commission will derive little savings from ETC because:

    a. Toll collection staff cannot be displaced (the same number of commissioners will be needed under all ETC scenarios as in the base case).
    b. Time spent on maintenance and token/coin counting should decrease, but there will be additional administration required for ETC, resulting in no significant net change in staffing.

3. The net benefits of ETC are highly dependent upon the assumed value of travel time. At the rate of approximately $17 CDN/hour, Scenario 8 (one additional dedicated ETC lane opened, and one manned lane converted to manned/ETC in each direction) is the optimum scenario. If this rate were less than $7 CDN/hour, then Scenario 2 (no ETC, two additional ACM lanes opened) would yield the greatest net benefit.

4. Alternate plaza configurations were highly effective in relieving rush hour congestion, but only marginally improved already smooth-flowing non-rush hour traffic conditions. Nearly 100 percent of the benefits of opening an extra toll booth in each direction (Scenario 2) were achieved during rush hours. All configurations yielded significant net benefits to society when compared to the base case.

The extra cost of installing ETC and lack of benefits for the bridge commission make ETC installation unprofitable. Due to age and increasing maintenance difficulties, it is necessary for the Halifax–Dartmouth Bridge Commission to replace their existing toll collection equipment. However, the only recommended change to current toll collection methods is to open Lane 8 from approximately 7 to 9 a.m. and Lane 7 from approximately 4 to 6 p.m. All other lanes and operations should continue as they do now. This will yield the vast majority of benefits realized in Scenario 2, and keep costs incurred by the bridge commission to a minimum.