A Simple Approach to Estimating Changes in Toll Plaza Delays

Dilruba Ozmen-Ertekin, Ph.D., PE  
Assistant Professor  
Engineering Department  
Hofstra University  
133 Hofstra University, Hempstead, NY 11549  
Phone: 516-463 6155, Fax: 516-463 4939  
email:eggdzo@hofstra.edu

Kaan Ozbay, Ph.D.  
Associate Professor  
Civil and Environmental Engineering Department  
Rutgers University  
623 Bowser Rd., Piscataway, NJ 08854  
Phone: 732-445 2792, Fax: 732-445 0577  
email:kaan@rci.rutgers.edu

Sandeep Mudigonda, Ph.D. Candidate  
Graduate Assistant  
Civil and Environmental Engineering Department  
Rutgers University  
623 Bowser Rd., Piscataway, NJ 08854  
Phone: 732-445 0579, Fax: 732-445 0577  
email:sandeepm@rci.rutgers.edu

Anne M. Cochran, M.S., EIT  
Urban Engineers, Inc.  
530 Walnut Street, Philadelphia, PA 19103  
Phone: 215-922 8081  
email:amcochran@urbanengineers.com

Paper Resubmitted for Presentation at the Transportation Research Board’s 87th Annual Meeting, 2008, Washington, D.C. and for Possible Publication in the 2008 Transportation Research Record Series

Resubmission Date: November 15, 2007

Word Count: 7431 (5931 words + 3 Tables + 3 Figures)
ABSTRACT

Toll plazas are important components of the road infrastructure especially in urban highways since they can have adverse capacity and safety impacts on traffic. However, they serve an important purpose namely revenue generation for highway agencies. Various traffic management and electronic toll collection strategies, including regular and high-speed E-ZPass, time-of-day pricing, are also implemented as part of toll plaza operations to change traffic supply and demand characteristics to improve network-wide level of service. In recent years, due to the increasing need to better assess the impact of toll plazas combined with these various traffic management strategies, customized or off-the-shelf microsimulation and macrosimulation models of toll plazas have been developed. This paper reviews the literature on both approaches. Then, a customized microscopic toll plaza model developed as an integrated part of PARAMICS microsimulation is compared with a relatively simple macroscopic model. This kind of macroscopic model that can estimate toll plaza delays is needed because it is extremely difficult and expensive to calibrate and implement microsimulation models when projects have severe budget and time constraints. Several NJ Turnpike toll plazas that were well validated and calibrated are used in the comparison. Sensitivity analysis is conducted using various other toll plazas to ensure the validity of the macroscopic model especially for cases where demand is reduced due to a real-time traffic management strategy. Results indicate that the macroscopic method is comparable (within average error 2.6%-6.4%) to the PARAMICS model when sufficient care is taken in selecting macroscopic and microscopic model parameters consistently.

Keywords: Electronic Toll Collection, Macroscopic Methods, Microsimulation, Toll Plaza Delays
INTRODUCTION

Toll plazas are important components of the road infrastructure especially in urban highways since they can have adverse capacity and safety impacts on traffic. However, they serve an important purpose namely revenue generation for highway agencies. Various traffic management and electronic toll collection (ETC) strategies, such as regular and high-speed E-ZPass, time-of-day pricing (TDP), are also implemented as part of toll plaza operations to change traffic supply and demand characteristics to improve network-wide level of service. In recent years, due to the increasing need to better assess the impact of toll plazas combined with these various traffic management strategies, customized or off-the-shelf microsimulation and macrosimulation models of toll plaza operations have been developed, as presented in the next section.

However, it is extremely difficult and expensive to calibrate and implement microsimulation models when projects have severe budget and time constraints. Therefore, it is necessary to develop alternative macroscopic approaches that are easy to use and inexpensive compared to the more complex microsimulation tools. Several studies, although not dealing with toll plaza operations specifically, used both macroscopic and microscopic tools to predict the traffic flow characteristics (e.g. 1,2). This kind of a comparative approach helps determine the validity of the macroscopic approaches.

Macroscopic models can also be easily embedded in 4-step demand forecasting models to estimate toll plaza delays and the impact of demand management strategies and technologies planned as part of toll collection operations. This will of course help the planners to easily perform sensitivity analysis of various alternatives without resorting to the microsimulation models that might not be feasible for large-scale state-wide studies.

Given this view, the main motivation of this paper is to estimate toll plaza delays without having to develop and use microsimulation models. More importantly, delay data at such facilities is either not always readily available or difficult to measure using conventional traffic detectors. Thus, the objectives of this paper are to:

1. propose the use of a set of delay equations very similar to Highway Capacity Manual’s (HCM2000) equations,
2. validate this relatively simple macroscopic model based on the results from a customized microscopic toll plaza model developed as an integrated part of PARAMICS microsimulation tool. Several NJ Turnpike toll plazas that were well validated and calibrated are used as the basis of this comparison,
3. conduct sensitivity analysis using various toll plazas at other locations to ensure the validity of the macroscopic model especially for cases where demand is reduced due to a real-time traffic management strategy.

Few studies, such as (5) proposed macroscopic delay estimation methodologies for the toll plazas and validated their results using calibrated microsimulation models. In (6) and (7) a macroscopic approach for delay estimation was developed, but comparison of the estimates to microscopic approaches was not done. Therefore, this study extends the current state of the art by presenting results on a comparative basis.

The next section provides a brief literature review. Then, the methodology for the macroscopic approach for toll plaza delay estimation is described, followed by a section describing the microscopic approach. The following section presents a comparison of the macroscopic and microscopic approaches using a number of toll plazas on the NJ Turnpike and Hudson River Crossings between NJ and NY. The validated macroscopic methodology is used to estimate the changes in toll plaza delays at Hudson River Crossings namely Bayonne, Goethals,
and George Washington Bridges, Holland and Lincoln Tunnels, and Outerbridge Crossing, due to TDP. Concluding remarks are presented in the last section.

LITERATURE REVIEW

This section provides a succinct summary of the recent literature on the subject of modeling toll plaza delays.

In (5), an analytical delay model, which estimates total delay by accounting for extra travel time due to deceleration, toll paying, acceleration and time spent waiting in queue, was formulated. To calibrate the model, a stochastic, microsimulation model was developed. The resulting incremental delay formulation was very similar to the formula given in (13), except it used a constant value of 0.425 as the multiplication of the incremental delay factor (k) and the upstream filtering/metering adjustment factor (I). The results showed that the delay model can yield estimates within 10% of simulated values. The author recommended that the delay model be used for preliminary screening of alternative designs and operations, and that further investigation be conducted to determine if the model can adequately estimate delay based upon field data.

In (11), the deployment of ETC was studied by developing a model to maximize social welfare associated with a toll plaza. A payment choice model was developed to estimate the share of traffic using ETC as a function of delay, price, and a fixed cost of acquiring the in-vehicle transponder. Assuming that welfare depends on the market share of ETC, and includes delay, gasoline consumption, toll collection costs, and social costs such as air pollution, the authors examined the best combination of ETC lanes and toll discount to maximize welfare. The generalized delay model suggested by (12) for the new HCM (13) was employed after a slight modification by taking both ‘k’ and ‘I’ as 1. An application to California’s Carquinez Bridge revealed that too many ETC lanes cause excessive delay to non-equipped users, whereas too high a discount costs the highway agency revenue.

In (6), a model that incorporates the HCM (13) delay model after a slight modification by taking both ‘k’ and ‘I’ as 1, was developed to estimate the social impacts of ETC and evaluate the financial benefits over the lifespan of the ETC investment.

In (7), a manual methodology was developed to determine capacity, queuing patterns and delays of toll plazas considering the approach roadway conditions and traffic demand characteristics, and applied to the Throgs Neck Bridge toll plaza.

Several studies in the literature, although not dealing with toll plaza operations specifically, used both macroscopic and microscopic tools to predict the traffic flow characteristics. (1), for example performed an extensive evaluation of the FasTrak system for an assessment of the numerous aspects of the I-15 High Occupancy Toll lane operations. One of the features of this evaluation was a comparison between macroscopic and microscopic approaches. In (2), whether commercially available traffic simulation models could be calibrated to yield accurate queue length and delay time predictions for planning purposes in freeway work zones was determined, using Highway Capacity Software, Synchro, Corsim, NetSim, and a macroscopic model called QueWZ92.

MACROSCOPIC APPROACH TO ESTIMATING TOLL PLAZA DELAYS

The total delay experienced at the toll plazas by each vehicle can be expressed as:

\[ d = d_d + d_i + d_p + d_a + d_q \]  

(1)
Deceleration delay is the extra travel time incurred while drivers decelerate before reaching a tollbooth. Equation 2 can be used to calculate the deceleration delay (5).

\[
d_d = P \frac{(V - V_b)^2}{2d_1 V} + (1 - P) \frac{(V - V_b)^2}{2d_2 V}
\]

where;
\(d_d = \) average deceleration delay in toll lane (s/veh)
\(P = \) proportion of noncommercial vehicles
\(V = \) free-flow speed (m/s)
\(V_b = \) speed at toll booth (m/s)
\(d_1 = \) deceleration rate of noncommercial vehicles (m/s²)
\(d_2 = \) deceleration rate of commercial vehicles (buses and trucks in this case) (m/s²)

Acceleration delay depends on the free-flow speed and the acceleration characteristics of vehicles, and is given as follows (5):

\[
d_a = P \frac{(V - V_b)^2}{2a_1 V} + (1 - P) \frac{(V - V_b)^2}{2a_2 V}
\]

where;
\(d_a = \) average acceleration delay in toll lane (s/veh)
\(a_1 = \) acceleration rate of noncommercial vehicles (m/s²)
\(a_2 = \) acceleration rate of commercial vehicles (m/s²)
Other variables as defined before.

According to the HCM (13), the incremental delay at signal-controlled intersections on principal arterials is:

\[
d = 900T \left( X - 1 + \sqrt{(X - 1)^2 + \frac{8kIX}{cT}} \right)
\]

where;
\(d = \) incremental delay (s/veh)
\(T = \) duration of analysis period (hr)
\(X = \) lane group volume/capacity ratio or degree of saturation
\(k = \) incremental delay factor that is dependent on traffic controller settings
\(I = \) upstream filtering/metering adjustment factor
\(c = \) lane group capacity (vph)
For this paper, however, because ‘k’ is a parameter to adjust for traffic actuated signals and ‘I’ is a parameter to adjust for filtering and metering by upstream signals, they can be taken as “0.5” (upper limit given in (13)) and “1”, respectively. As a result, the incremental delay equation used here reduces to the form given in Equation 5, which expresses the incremental delay experienced by each vehicle in the toll lane due to random variations in toll processing times and vehicle arrivals. Equation 5 assumes that there are no queuing vehicles at the beginning of the analysis period.

\[
d_i = 900T \left( X - 1 \right) + \sqrt{(X - 1)^2 + \frac{4X}{C.T.N}}
\]

where;
\( d_i \): average incremental delay in toll lane (s/veh)
\( T \): analysis period (hr)
\( X \): volume/capacity ratio
\( C \): capacity (vehicles per lane per hour, or vplph)
\( N \): number of toll lanes

The NJ Turnpike toll plazas used as the basis of comparison between macro and micro approaches presented here can be considered as isolated intersections, so, the use of an ‘I’ value equal to 1 is appropriate. However, the Hudson River crossings, which were used for further comparisons, are more prone to upstream conflicts due to nearby traffic signals, so, lower I values can be used in accordance with the specifications in (13) by taking into consideration the upstream degree of saturation. However, due to unavailability of data for the upstream conditions, I=1 was used for all the toll plazas studied here.

In order to take any delay due to the presence of initial queues at the toll plaza at the beginning of the analysis period into account, delay component \( d_q \) from (13) is used here as \( d_q \). For further details on this delay component, readers are kindly asked to refer to Chapter 16, Appendix F in (13).

\[
d_q = \frac{1800Q_b(1+u)}{cT}
\]

where,
\( d_q \): average initial queue delay in toll lane (s/veh)
\( t \): duration of oversaturation within T (hr)
\( u \): delay parameter
\( Q_b \): Total number of vehicles present at the toll lanes at the beginning of T (veh)
\( c \): toll lane group capacity (vph)

The service time required to pay the toll results in an additional delay to each vehicle, and is dependent on the method of payment (ETC or manual).

In this paper, the length of the analysis is kept at one hour, and the incremental delay was calculated for each hour and then summed to determine the total incremental delay for the peak period. Breaking up the entire four-hour peak period into one-hour blocks increases the accuracy of the macroscopic model.

The macroscopic approach described here can be implemented very easily by incorporating the delay formulations into a spreadsheet. Sensitivity analysis can also be
performed very easily and in a few minutes just by varying the values of the desired variables, whereas each run takes about 1 hour in PARAMICS microsimulation.

**MICROSCOPIC MODELING OF TOLL PLAZAS**

The major advantage of microscopic traffic simulation models is the level of detail in the modeling procedure. Modeling the dynamics of traffic flow is essential in the evaluation of the impacts of various operational strategies. Microsimulation provides necessary tools for this approach. Quadstone PARAMICS is a widely used microsimulation software package with a wide range of functionalities such as the default simulation logic in car following, lane changing, route choice, etc., that can be modified using Application Programming Interface (API).

Most of the existing microsimulation packages do not have an accurate toll plaza model. Hence, many researchers have developed customized toll plaza simulation models (e.g. 22,23,24).

Although PARAMICS has some of the basic features that can be used to build a toll plaza model, additional work using the API had been performed to represent toll plaza operations accurately by (16) using NJ Turnpike data. The main feature of this approach is the lane changing logic involved at the toll plaza. The lane choice decision in PARAMICS is performed two links before a junction. A toll plaza consists of many links with varying number of lanes. To model this in PARAMICS, it is necessary to have a number of small links with different number of lanes. Additionally, toll plaza configurations in the NJ Turnpike is such that, after crossing the toll plaza, the vehicles traveling north or south have to choose an appropriate ramp to enter the freeway. The lane choice logic in PARAMICS, when encountered by a decision of different paths as described above, will fail in the case of a toll plaza with many short links. Figure 1 (16) illustrates the process of improved lane choice logic.

Toll plazas on the NJ Turnpike are not barrier toll plazas, but are located at separate areas where users enter/exit the freeway (14). However, they are important features of the network as they affect the travel times between origin and destination (OD) pairs. The accuracy of a toll plaza model is determined by the following features of the toll plaza incorporated in the modeling procedure:

- Geometry
- Lane configuration (Cash or ETC)
- Service time distribution
- Arrival distribution
- User behavior

A very important aspect of modeling traffic using microsimulation is the calibration and validation of the models using real-world data. There are many model parameters that have to be adjusted to replicate performance closer to the real-world. In (16), the geometry was obtained from satellite images and incorporated as overlays in the model. Service time distributions were collected from videographic data collected at two toll plazas (15W and 16E) on the NJ Turnpike (17). For the simulation of facilities such as Holland Tunnel, Lincoln Tunnel the average service times from the exit toll plazas of 15W and 16E have been used. This is because the Cash users do not carry any ticket, but they only pay the requisite toll when they cross the toll plaza.

In the development of the customized toll plaza model, (16) used the disaggregate vehicle-by-vehicle electronic transaction data at each toll plaza. This dataset contains type of the vehicle, entry and exit times of the vehicle when it crosses the toll plaza, and the lanes used. From this data, the number of E-ZPass and Cash users was directly available for January-May,
2005 for seven days in a week for the entire day. From this raw data, O-D demand in terms of number of E-ZPass and Cash users was extracted for the AM (7AM-9AM) and PM (4:30PM-6:30PM) peak, and AM (6-7AM, 9-10AM), and PM (3:30-4:30PM, 6:30-7:30PM) peak shoulder periods for a typical weekday (8). This dataset replicates the arrival distribution at the toll plazas in the most accurate fashion. Although it would be ideal to collect the gap-acceptance and lane choice behavior data at the toll plaza, it is a very time-consuming and difficult to obtain such datasets. In (16) the toll plaza model was validated for the travel time between ODs, volumes on the freeway mainline volume, and proportion of lane usage at the toll plaza.

FIGURE 1 Logic of the toll plaza lane changing behavior in PARAMICS (16).

COMPARISON BETWEEN MACROSCOPIC AND MICROSCOPIC APPROACHES

Comparison Using NJ Turnpike Data
The validity of macroscopic methodology was tested using data from the Interchanges 12, 13, and 14 of the NJ Turnpike and by comparing the results to PARAMICS model results, which are the average of three simulation runs, since it has been observed that the deviation in the results is
not significant (less than 5%) in some of the previous executions of the simulation runs. The following is some of the input data used, all obtained from (16) unless stated otherwise:

- **Service time, $d_p$:** 5.7 seconds for Cash, 3 seconds for E-ZPass, based on a previous study of the NJ Turnpike (17).
- **Capacity, $C$** of E-ZPass and Cash toll lanes, 1150 vplph and 375 vplph, respectively, (using the average observed capacity values obtained from NJ Turnpike Authority (NJTA) through an e-mail correspondence in 2002). These capacity values fall in the range of values used in several other similar studies in the literature. For example, (7), who modeled Throgs Neck Bridge toll plaza in NY, stated that, during AM peak, Cash booths processed 176-275 vph with an average of 230 vph, and ETC booths processed 343-713 vph with an average of 527 vph, based on count data. In (11), the capacity of the ETC lanes on the Carquinez Bridge, CA, was determined by the minimum headway of 2.4 seconds, which meant a capacity of 1500 vph. Using a validated simulation model, (25) estimated the maximum throughput of a manned tollbooth as 408 vph, and the potential capacity of an exclusive M-Tag (ETC) tollbooth was estimated as 1,025 vph.

- **Free flow speed, $V$:** 13.4 m/s (30 mph) (posted).
- **Speed at toll booth, $V_b$:** 0 for Cash, 5.36 m/s (12 mph) for E-ZPass (it was observed that the speed varies from 30 mph to about 7 mph at the exit line of the toll plaza, so an approximate average value of 12 mph was taken here).
- **Based on the mean values used in PARAMICS,** the deceleration rate for noncommercial vehicles, $d_1$, the deceleration rate for commercial vehicles, $d_2$, the acceleration rate for noncommercial vehicles, $a_1$, and the acceleration rate for commercial vehicles, $a_2$ were taken as 4.87 m/s$^2$, 3.47 m/s$^2$, 2.71 m/s$^2$, and 1.19 m/s$^2$, respectively.
- **Analysis period, $T$:** 1 hr.
- **Number of toll lanes, $N$:** Exit 12: 1 lane for Cash and E-ZPass each
  - Exit 13: 3 lanes for Cash and E-ZPass each
  - Exit 14: 4 lanes for Cash and E-ZPass each
- The demand (volume, vph) (16):
  - Exit 12: AM Peak: 160 for Cash, 298 for E-ZPass
  - Exit 13: AM Peak: 609 for Cash, 1130 for E-ZPass
  - Exit 14: AM Peak: 1042 for Cash, 1935 for E-ZPass
- **Initial queue, $Q_b$:** (Assumed values): AM Peak: 5 veh/Cash-lane, 4 veh/E-ZPass-lane

The lane configurations at Interchange 14 along the NJ Turnpike and the three of the Hudson River Crossings are shown in Figure 2.

The results (Table 1) are comparable (mean absolute error is 2.56%) when sufficient care is taken in selecting the macroscopic and microscopic model parameters consistently. This relatively small error might be attributable to the facts that macroscopic approach does not take lane configurations into consideration, and uses deterministic acceleration/deceleration rates whereas PARAMICS uses probabilistic rates throughout the simulation.
FIGURE 2 Toll plaza lane configurations used in the comparison (Green:Cash, Orange:Mixed, Purple:E-ZPass).
TABLE 1 Comparison of Macro and Micro Approaches

<table>
<thead>
<tr>
<th>Toll Plaza</th>
<th>Average Weekday AM Peak Delay (s/veh)</th>
<th>Total Average Weekday AM Peak Delay (hours)</th>
<th>Absolute Error (for Avg. Delay)</th>
<th>Average Weekday PM Peak Delay (s/veh)</th>
<th>Total Average Weekday PM Peak Delay (hours)</th>
<th>Absolute Error (for Avg. Delay)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bat 1.2</td>
<td>21.63</td>
<td>22.39</td>
<td>1.17</td>
<td>1.21</td>
<td>3.32%</td>
<td></td>
</tr>
<tr>
<td>Bat 1.3</td>
<td>19.87</td>
<td>20.47</td>
<td>4.11</td>
<td>4.36</td>
<td>3.02%</td>
<td></td>
</tr>
<tr>
<td>Bat 1.4</td>
<td>23.4</td>
<td>23.71</td>
<td>8.1</td>
<td>8.53</td>
<td>1.35%</td>
<td></td>
</tr>
<tr>
<td>Holland T.</td>
<td>38.39</td>
<td>39.65</td>
<td>14.13</td>
<td>14.29</td>
<td>1.97%</td>
<td>145.37</td>
</tr>
<tr>
<td>Lincoln T.</td>
<td>84.25</td>
<td>86.74</td>
<td>47.53</td>
<td>48.33</td>
<td>2.96%</td>
<td>82</td>
</tr>
<tr>
<td>Goethals B.</td>
<td>76.04</td>
<td>79.36</td>
<td>16.79</td>
<td>17.47</td>
<td>4.37%</td>
<td>401.51</td>
</tr>
</tbody>
</table>

Comparison Using Hudson River Crossings Data

The validity of macroscopic delay calculations was further tested using data from the Holland and Lincoln Tunnels and the Goethals Bridge, and the results were compared to the delays estimated by PARAMICS. Some of the input data used in this comparison are as follows:

- **Service time, \( d_p \):** 9.6 seconds for Cash, 3 seconds for E-ZPass, simply taken as the inverse of the capacity. This approach is recommended for the cases where field observations are not available.

- **Capacity, \( C \):** of E-ZPass and Cash toll lanes, 1150 vph and 375 vph, respectively, (using the average observed capacity values obtained from NJTA through an e-mail correspondence in 2002).

- **Free flow speed, \( V \):(18):** Goethals: 22.35 m/s (50 mph) before the plaza, 20.12 m/s (45 mph) after the plaza
  
  Holland: 15.65 m/s (35 mph)
  
  Lincoln: 20.12 m/s (45 mph) before the plaza, 15.65 m/s (35 mph) after the plaza

- **Speed at toll booth, \( V_b \):** 0 for Cash, 6.71 m/s (15 mph) for E-ZPass (posted).

- Based on the acceleration and deceleration rates reported in the literature that varies between 0.56-2.69 m/s\(^2\) for acceleration rates and between 0.56-3.09 m/s\(^2\) for deceleration rates \((5,15,19,20)\), the deceleration rate for noncommercial vehicles, \(d_1\), the deceleration rate for commercial vehicles, \(d_2\), the acceleration rate for noncommercial vehicles, \(a_1\), and the acceleration rate for commercial vehicles, \(a_2\) are taken as 2.4 m/s\(^2\), 1.48 m/s\(^2\), 1.5 m/s\(^2\), and 0.97 m/s\(^2\), respectively.

- **Analysis period, \( T \):** 1 hr.

- **Number of toll lanes, \( N \):(18):** There are Mixed (allowing both E-ZPass and Cash payments) and E-ZPass-only lanes at the toll plazas of the Hudson River Crossings.

  Goethals: 3 lanes Mixed, 5 lanes for E-ZPass
  
  Holland: 4 lanes Mixed, 5 lanes for E-ZPass
  
  Lincoln: 7 lanes Mixed, 6 lanes for E-ZPass

- **Total demand (volume, \( v_{ph} \)):** Obtained from \((21)\) and \((3)\).

  Goethals: AM Peak: 3041 for Mixed, 3713 for E-ZPass
PM Peak: 5432 for Mixed, 6786 for E-ZPass
Holland: AM Peak: 5087 for Mixed, 5864 for E-ZPass
PM Peak: 5896 for Mixed, 4725 for E-ZPass
Lincoln: AM Peak: 7544 for Mixed, 11003 for E-ZPass
PM Peak: 5379 for Mixed, 5038 for E-ZPass

Initial queue, $Q_b$ (Assumed values): AM Peak: 5 veh/Cash-lane, 4 veh/E-ZPass-lane
PM Peak: 2 veh/Cash-lane, 1 veh/E-ZPass-lane

In this study, when estimating the delays with the macroscopic approach for the toll plazas containing Mixed lanes, Mixed lanes were treated as Cash lanes since the E-ZPass users tend to use E-ZPass-only lanes in general. This tendency can be attributable to the perception of the E-ZPass users that delays can be higher at Mixed lanes. In fact, the lane usage data for June 12, 2006 at the entry toll plaza at interchange 11 of NJ Turnpike during peak hours showed that only 4.1% of the total E-ZPass users used the Mixed lanes. It should be noted that there is a distinction between entry and exit toll plazas on the NJ Turnpike: At the entry, Cash vehicles stop to receive a toll ticket only, whereas at the exit, they stop to pay the toll and wait to receive the change, if any. This results in a higher transaction time, hence longer delays and queues for Cash vehicles at the exit toll plazas. Thus, it is plausible to say that E-ZPass users have a lesser probability (than 4.1%) of choosing a Mixed lane at the exit toll plaza. Since on the Hudson River Crossings the Cash vehicles stop at the toll plazas to pay the toll, these toll plazas are equivalent to the exit toll plazas of the NJ Turnpike. Therefore it can be deduced that the proportion of E-ZPass users using Mixed lanes at the toll plazas of the Hudson River Crossings could be even less than 4.1%, which justifies the treatment of Mixed lanes as Cash-only lanes in the macroscopic approach in this study.

The results (Table 1) from the macro and micro-level approaches for the Holland and Lincoln Tunnels, and the Goethals Bridge compare very closely, especially for the AM peak period.

DELAY CHANGES ESTIMATED USING MACROSCOPIC MODEL
The macroscopic methodology that was validated by comparison with the well calibrated microsimulation model as discussed in the previous sections will now be used to estimate the changes in toll plaza delays due to changes in demand resulting from the Time-of-Day Pricing (TDP) implemented at the Hudson River Crossings. It is important to note that delays presented here are not validated using real-world data, thus might not reflect observed delays that were not available to the research team. Thus, this section mainly illustrates one of the ways of using macroscopic equations described in this paper to evaluate various demand management strategies.

TDP involves imposing higher toll rates during peak periods to reduce traffic congestion. TDP was introduced at Hudson River Crossings on March 25th, 2001, for the users of E-ZPass.

The changes in delays were estimated for all the Hudson River Crossings, not just for the 3 crossings used in validation process presented in the previous section. Some of the input data for the additional facilities used in this analysis are as follows:

Free flow speed, $V$ (18): Bayonne, GWB (Upper and Lower Levels, and PIP): 24.59 m/s (55 mph)
Outerbridge: 20.12 m/s (45 mph)

Number of toll lanes, $N$ (18): Bayonne: 2 lanes Mixed, 1 lane for E-ZPass
GWB UL and LL: 6 lanes Mixed, 6 lanes for E-ZPass  
GWB PIP: 3 lanes Mixed, 4 lanes for E-ZPass  
Outerbridge: 5 lanes Mixed and E-ZPass each

- **Total demand (volume, vph):** Obtained from (21) and (3). Demand data for July 2001 only is shown below for brevity.

  Bayonne: AM Peak: 463 for Mixed, 1133 for E-ZPass  
  PM Peak: 803 for Mixed, 2875 for E-ZPass  
  Off-Peak: 1573 for Mixed, 3510 for E-ZPass  

  GWB UL: AM Peak: 4761 for Mixed, 11503 for E-ZPass  
  PM Peak: 7075 for Mixed, 8703 for E-ZPass  
  Off-Peak: 19949 for Mixed, 21459 for E-ZPass  

  GWB LL: AM Peak: 3555 for Mixed, 11015 for E-ZPass  
  PM Peak: 5895 for Mixed, 9099 for E-ZPass  
  Off-Peak: 12273 for Mixed, 18555 for E-ZPass  

  GWB PIP: AM Peak: 1238 for Mixed, 6147 for E-ZPass  
  PM Peak: 1740 for Mixed, 3773 for E-ZPass  
  Off-Peak: 3146 for Mixed, 8026 for E-ZPass  

  Outerbridge: AM Peak: 2147 for Mixed, 6611 for E-ZPass  
  PM Peak: 3168 for Mixed, 7913 for E-ZPass  
  Off-Peak: 8130 for Mixed, 16469 for E-ZPass  

- **Initial queue, \(Q_b\) (Assumed values):** AM Peak: 5 veh/Cash-lane, 4 veh/E-ZPass-lane  
  PM Peak: 2 veh/Cash-lane, 1 veh/E-ZPass-lane  
  Weekend Peak: 3 veh/Cash-lane, 2 veh/E-ZPass-lane  
  Off-Peak: 1 veh/Cash-lane, none on E-ZPass lane

  Delays were calculated with the macroscopic approach using July 2000 (before TDP) and July 2001 (after TDP) data, for the weekday and weekend peak and off-peak periods. The peak hours for the facilities considered are 6AM-9AM and 4PM-7PM on weekdays. Weekend peak hours are from 12PM to 8PM. The off-peak hours are the rest of the day when the peak periods are subtracted.

  By considering the time periods both before and after the implementation of TDP, a comparison could be made and the effect of TDP policy on possibly decreasing toll plaza delays can be better understood. As verified through an ANOVA test in (3), seasonal variations in the demand data were found to be negligibly small.

  As can be seen in Table 2, TDP resulted in significant reductions (>10%) in delay (gray cells), especially for the weekday afternoon peak and weekend peak periods.
TABLE 2 Average Delay Estimated with Macroscopic Equations (s/veh)

<table>
<thead>
<tr>
<th>Plaza</th>
<th>Weekday</th>
<th>AM Peak</th>
<th>Before TDP</th>
<th>After TDP</th>
<th>PM Peak</th>
<th>Before TDP</th>
<th>After TDP</th>
<th>Off-Peak</th>
<th>Before TDP</th>
<th>After TDP</th>
<th>Peak</th>
<th>Before TDP</th>
<th>After TDP</th>
<th>Off-Peak</th>
<th>Before TDP</th>
<th>After TDP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bayonne</td>
<td></td>
<td>37.52</td>
<td>37.76</td>
<td>37.73</td>
<td>38.28</td>
<td>35.81</td>
<td>35.57</td>
<td>34.7</td>
<td>34.44</td>
<td>34.46</td>
<td>34.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goethals</td>
<td></td>
<td>76.03</td>
<td>46.15</td>
<td>401.5</td>
<td>63.11</td>
<td>82.88</td>
<td>38.38</td>
<td>593.54</td>
<td>192.8</td>
<td>84.15</td>
<td>55.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWB UL</td>
<td></td>
<td>38.32</td>
<td>36.49</td>
<td>112.8</td>
<td>37.32</td>
<td>38.32</td>
<td>36.24</td>
<td>207.34</td>
<td>39.15</td>
<td>45.94</td>
<td>36.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWB LL</td>
<td></td>
<td>36.84</td>
<td>35.85</td>
<td>365.46</td>
<td>35.35</td>
<td>36.4</td>
<td>37.5</td>
<td>58.59</td>
<td>35.82</td>
<td>35.27</td>
<td>34.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWB PIP</td>
<td></td>
<td>35.19</td>
<td>34.3</td>
<td>35.32</td>
<td>34.39</td>
<td>37.28</td>
<td>35.83</td>
<td>35.09</td>
<td>34.56</td>
<td>37.83</td>
<td>35.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lincoln</td>
<td></td>
<td>84.25</td>
<td>30.34</td>
<td>82</td>
<td>31.78</td>
<td>26.84</td>
<td>26.47</td>
<td>28.54</td>
<td>27</td>
<td>26.82</td>
<td>26.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holland</td>
<td></td>
<td>38.89</td>
<td>29.71</td>
<td>145.57</td>
<td>34.66</td>
<td>55.77</td>
<td>27.16</td>
<td>274.66</td>
<td>41.37</td>
<td>104.94</td>
<td>30.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer</td>
<td></td>
<td>30.75</td>
<td>30.61</td>
<td>30.38</td>
<td>29.68</td>
<td>30.32</td>
<td>30.14</td>
<td>30.85</td>
<td>29.97</td>
<td>29.69</td>
<td>29.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sensitivity Analysis

Knowing that TDP policies are associated with offering discounted tolls for eligible users during off-peak periods; this section explores various TDP scenarios by considering additional hypothetical toll discounts, which would result in demand shifts from Cash to E-ZPass, consequently reducing delays due to lower processing times associated with E-ZPass. So, when additional discounts are applied, it is assumed here that the total existing demand will remain unchanged and only a shift from Cash to E-ZPass will occur. Figure 3, which shows data for all 6 of the Hudson River Crossings combined, supports this assumption; even though the demand for E-ZPass consistently increased, the total demand seemed to remain relatively constant. This indicates a shift from Cash to E-ZPass usage.

FIGURE 3 E-ZPass usage and total demand trends.

To compute the changes in E-ZPass demand that will result from additional toll discounts, price elasticities estimated in (3) were used. Since (3) provides elasticities for noncommercial vehicles only, delays were re-estimated in this section for the purposes of the
sensitivity analysis. For the sensitivity analysis, weekday off-peak (3PM-4PM) period with July 2001 data was considered.

To interpret the results given in Table 3, consider Holland Tunnel. The amount of delay for 3PM-4PM period on a weekday in July 2001 was 28.72 s/veh (for noncommercial vehicles only). This value is already less than the delay experienced a year before in July 2000 (before TDP) at Holland Tunnel (that value not reported in this paper). But, in addition to the discounts offered by the existing TDP program, if an extra 10% discount is applied to off-peak tolls, delays for Holland Tunnel reduces to 26.53 s/veh. Thus, a 10% extra discount in tolls translates into 7.63% reduction in delays for the Holland Tunnel.

### TABLE 3 Percent Reduction in Delay in Response to TDP

<table>
<thead>
<tr>
<th>Plaza</th>
<th>Delays (sec/veh) when Toll Prices Reduced by an Additional:</th>
<th>% Change in Delays when Toll Prices Reduced by an Additional:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Bayonne</td>
<td>33.57</td>
<td>33.53</td>
</tr>
<tr>
<td>Goethals</td>
<td>87.64</td>
<td>39.14</td>
</tr>
<tr>
<td>GWB UL</td>
<td>34.12</td>
<td>33.51</td>
</tr>
<tr>
<td>GWB LL</td>
<td>32.91</td>
<td>32.52</td>
</tr>
<tr>
<td>GWB PIP</td>
<td>33.94</td>
<td>33.7</td>
</tr>
<tr>
<td>Lincoln</td>
<td>25.83</td>
<td>25.66</td>
</tr>
<tr>
<td>Outer</td>
<td>28.48</td>
<td>28.31</td>
</tr>
<tr>
<td>Avg.</td>
<td>0</td>
<td>-8.50</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

This study showed that toll plaza delays can be estimated accurately by using relatively simple macroscopic models, rather than more complicated and costly microsimulation tools. The accuracy of the delays estimated in this study was validated using a well-calibrated microsimulation toll plaza model implemented in PARAMICS. Comparison of the results of the macroscopic delay estimation with the microsimulation results indicated that both approaches yield similar results within an average error of 3.1%-6.4% for the Hudson River Crossings and within an average error of 2.6% for the NJ Turnpike interchanges. This justifies the use of macroscopic delay equations in lieu of more complex microsimulation approaches that are both labor intensive and costly to develop. The macroscopic approach described here can be implemented very easily by incorporating the delay formulations into a spreadsheet. Sensitivity analysis can also be performed very easily and in a few minutes just by varying the values of the desired variables, whereas each run takes about 1 hour in PARAMICS microsimulation.

There are, however, certain ways in which the macroscopic approach described here can be further improved to keep the discrepancies between the macro and micro approaches to a minimum:

- Instead of using deterministic values, variations can be incorporated into the delay equations to better reflect variability, for example in the deceleration/acceleration rates.
- Instead of taking the upstream adjustment factor, I as 1, a more precise value can be calculated using the upstream degree of saturation.
- Instead of assuming that Mixed toll lanes are solely used by Cash users, a more realistic utilization rate (e.g. 10% E-ZPass, 90% Cash users) can be assumed and incorporated into the equations.
More detailed comparisons should be performed using data from other toll plazas at different locations and with different geometries to draw more reliable conclusions about the accuracy and general applicability of the macroscopic models.

The results from the application of the macroscopic methodology to estimate the changes in toll plaza delays due to changes in demand resulting from TDP implemented at the Hudson River Crossings indicated that, TDP resulted in quite significant reductions (>10%) in delays.

The results from the sensitivity analysis indicated that, in addition to the discounts offered by the existing TDP program, if an extra 10% discount is applied to off-peak tolls, the delays reduce by 8.5% on average for the facilities analyzed.

The macroscopic approach shown in this paper has the potential of providing the traffic engineers and decision makers with a good idea about the delay savings due to the operational changes such as E-ZPass, TDP. It is however important to note that the delays presented in this paper are not validated using real-world data and thus might not reflect real-world delays that were not available to the research team. Delays were obtained from the microscopic PARAMICS model, which was calibrated using toll plaza data from previous studies (21,4) and network-wide flows and travel times. Therefore, a natural extension of this work would be to compare model predictions with real delays obtained from an extensive data collection effort that can be done at toll plazas to better assess the accuracy of delay estimates from the macroscopic models described here.

REFERENCES


