Effects of the Open Road Tolling on Safety Performance of Freeway Mainline Toll Plazas

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ABSTRACT
Advances of Intelligent Transportation Systems (ITS) technologies promoted the implementation of open road tolling (ORT) on tolled freeways worldwide. This new tolling solution converts existing barrier tollbooths to express lanes capable of collecting tolls at high-speeds. ORT has demonstrated numerous benefits in reducing traffic congestion and air pollution. However, effects of ORT on safety are still not clear, as most of ORT systems have only been operated for a relatively short period of time. Therefore, this study aims to evaluate the safety impacts of ORT by studying locations where such tolling solution was recently deployed on the Garden State Parkway in New Jersey. Multiple-year crash data at the toll plazas before-after the implementation of the ORT systems were used for analysis. Full Bayes methodology is employed to estimate crash frequency models as a function of traffic and toll plaza configurations. These models were used to estimate the crash frequency assuming that the ORT systems were not installed. Then, these estimations were compared with the observed number of crashes occurred after the deployment of the ORT systems. Individual comparisons show that crash reductions are observed at most of the toll plazas. The overall comparison shows that crashes at locations where ORT systems were deployed are decreased by about 24 percent after deployment of these systems. It can thus be concluded that the use of ORT is a beneficial solution towards improving toll road safety. From an implementation point of view, the analyses results indicate that special attention should be paid to operational elements such as signage, diversion and merge designs of the ORT systems.
INTRODUCTION

Open road tolling (ORT) is a new generation of tolling solution that will eventually lead to a conversion of conventional toll plazas to barrier-free electronic toll collections in the future. By design, ORT consisting of high-speed (express) electronic toll collection (ETC) lanes allows vehicles to electronically and automatically pay tolls without slowing down from highway speeds. Typically, there are two types of implementation of ORT (1). The first type is the all-electronic ORT which completely replaces barrier tollbooths by express ETC lanes (2, 3). Without the presence of tollbooths, this type of ORT design enables automatic debiting via in-vehicle transponders (e.g., E-ZPass tags) or other automatic vehicle identification (AVI) technologies. The second is the interim type of ORT implementation, which is being deployed by many toll authorities. It installs express ETC lanes by retrofitting existing tollbooths to permit high-speed non-stop toll collection for ETC users and other registered users only (1, 4). Cash or coin users are still diverted to use remaining barrier booths off the express ETC lanes.

In the United States, many highway authorities in states like New Jersey, Florida and Illinois have implemented the ORT concept in recent years (e.g., 5-7). Demonstration projects have shown that the implementation of ORT is an effective means of relieving congestion. For example, Klodzinski et al. (1) evaluated the addition of ORT to a mainline toll plaza in Florida and found that installation of express ETC lanes reduced delays by 49.8 percent for cash users and by 55.3 percent for automatic coin machine (ACM) users. According to Levinson and Odlzyko (8), express ETC lanes of ORT can increase throughput, from 350 to 400 vehicles per hour per lane with manual collection up to 2200 vehicles per hour per lane. The use of ORT has also been shown to significantly reduce emissions. For instance, Lin and Yu (9) quantified various ORT deployment scenarios on Illinois toll highways and suggested that the near roadside carbon monoxide concentration levels and diesel particulate matter emissions can be reduced by up to 37 percent and 58 percent, respectively.

While ORT can sharply reduce transaction-related delays and pollution at toll plazas, safety impacts of retrofitting existing toll plazas and installing express ETC lanes, however, is still not so clear. ORT systems can be deemed safer since high-speed tolls avoid the safety deficiency of barrier toll plazas as they eliminate many stop-and-go traffic, dangerous interactions and distractions (10). On the other hand, diverging and merging of vehicles that use express ETC lanes at higher speeds might increase traffic conflicts (e.g., 11, 12). Cash and coin users must exit to use the barrier tollbooths and then merge with high-speed users on express lanes. These maneuvers may raise more safety issues. Unlike those easily measurable benefits such as capacity improvement and reduction of costs in toll collection (e.g., 13-16), it is difficult to evaluate safety performance of the new tolling solution shortly after its implementation because of the random and rare occurrence of motor vehicle crashes. Quantifying safety performance of ORT requires long-term crash data collected at toll plazas with and without the deployment of ORT.

This study aims to evaluate the impact of implementing ORT on crash rates at toll plazas by using extensive data collected at multiple mainline toll plazas with and without the deployment of express ETC lanes on Garden State Parkway in New Jersey. The crash data available in this study cover the period from January 2001 to December 2009. Therefore, safety performance of toll plazas with and without express ETC lanes can be analyzed and compared using these multiple-year crash data (17).
OPEN ROAD TOLLING IN NEW JERSEY

Gardens State Parkway (GSP) is a 172.4-mile limited-access toll parkway with 359 exits and entrances. Over 380 million vehicles travel the GSP which stretches the length of New Jersey (NJ) from the New York (NY) state line at Montvale to Cape May at the southern tip of the state. Tolls are collected at 50 locations, including 11 mainline toll plazas and 39 on entrance and exit ramps (18). It is among America’s busiest highways, serving users from NJ and NY’s most marketable communities (19, 20).

The GSP operator (GSP was operated by the NJ Highway Authority (NJHA) until 2003 and later by the NJ Turnpike Authority (NJTA)) always focused on using new toll collection technologies to improve tolling efficiency and reduce congestion. After the first toll collected manually in 1954, automatic coin machines (ACM) were introduced in early 1950s and had spread to most toll plazas and ramps on the Parkway by 1959 (21). When a toll increased beyond the quarter, tokens were introduced in the early 1980s. They continued to be available until January 2002 and ceased to be accepted in payment in January 2009 (21). Regular (low-speed) ETC system was implemented in 1999. The entire ETC system was completed in August 2000 (20). The ETC system has been widely adopted by travelers with an ETC penetration rate beyond 70 percent on GSP (22).

In 2001, the state government issued an order to promote a 10-year congestion relief plan for GSP (13). Under the plan, elimination of mainline barriers in one direction and use of express ETC lanes of ORT in the other were recommended. By 2010, all mainline barriers except Toms River were converted to one-way tolling (express ETC lanes were added to both directions at the Toms River toll plaza). Between 2004 and 2006, the open road tolling program was implemented. Express ETC lanes of ORT have been installed at a number of toll plazas listed in TABLE 1.

<table>
<thead>
<tr>
<th>Toll Plaza</th>
<th>Milepost</th>
<th>ORT Operation Date</th>
<th>No. of Express ETC Lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape May NB</td>
<td>19.4</td>
<td>May 2006</td>
<td>2</td>
</tr>
<tr>
<td>Toms River NB</td>
<td>84.7</td>
<td>May 2005</td>
<td>2</td>
</tr>
<tr>
<td>Toms River SB</td>
<td>84.7</td>
<td>May 2005</td>
<td>2</td>
</tr>
<tr>
<td>Asbury Park NB</td>
<td>104.0</td>
<td>May 2005</td>
<td>3</td>
</tr>
<tr>
<td>Raritan SB</td>
<td>125.4</td>
<td>May 2005</td>
<td>5</td>
</tr>
<tr>
<td>Pascack Valley NB</td>
<td>166.1</td>
<td>January 2004</td>
<td>2</td>
</tr>
<tr>
<td>Pascack Valley SB</td>
<td>166.1</td>
<td>January 2004</td>
<td>2</td>
</tr>
</tbody>
</table>

Installation of express ETC lanes at the Pascack Valley toll plaza in January 2004 marks a major milestone of ORT deployment on GSP. FIGURE 1 shows the progression of toll collection at the toll plaza. The conventional toll plaza with seven tollbooths in one direction was retrofitted to an interim version of ORT system, which allows ETC drivers to drive at 55mph through two high-speed lanes in each direction. Followed this demonstration project, this type of ORT system has been successfully deployed at several other sites listed in TABLE 1. FIGURE 2 shows an example of the layout of the converted plaza. Signs are installed upstream of the toll plaza to guide the selection of tollbooths. Upon the operation of such ORT system, electronic readers mounted on the gantry automatically charge the ETC vehicles. Meanwhile, overhead cameras capture the license plates of vehicles without transponders (e.g., E-ZPass tag). Cash and coin users are diverted to use barrier tollbooths. The new ORT system has been widely accepted as over 90 percent E-ZPass vehicles use the high-speed lanes on GSP. It is estimated that express ETC lane can process about 800 more vehicles per hour than traditional ETC lanes (10). Compared to the observed benefits such as capacity improvement and reduction of costs in...
toll collection (e.g., 10, 13 & 14), little information about the safety impact of the deployed ORT system is available.

FIGURE 1 Toll collection evolution at Pascack Valley toll plaza (Source: 10, 14)

FIGURE 2 Separation between barrier tollbooths and express E-ZPass lanes at Cape May Northbound toll plaza (Source: Google Map)
SAFETY PERFORMANCE MODELING

Data Description

To investigate crash characteristics at various toll plaza locations, data from a number of resources were collected. The toll plaza configurations and monthly average daily traffic (MADT) data for GSP toll plazas between January 2001 and December 2009 were obtained from the New Jersey Turnpike Authority (NJTA). The corresponding crash records for toll areas are obtained from the raw crash database of the New Jersey Department of Transportation (NJDOT). The records provide detailed information on each crash such as the time, location, collision type and severity etc. In order to capture the impact of toll plaza, it is necessary to limit the toll plaza analysis to certain section. Generally, crash data are analyzed from sections of 0.5 miles or longer (e.g., 23, 24). Considering the signposting distances and physical lengths of the toll plazas on GSP, toll plaza major impact area is assumed to be one mile which covers 0.5 miles before and after the tollbooths, respectively. Crashes occurred within the impact area of each toll plaza were extracted from the raw crash records. To avoid the influence of construction, data of one-year before the operation of the ORT systems were excluded from analysis. TABLE 2 presents the mean and standard deviation (SD) of MADT and the corresponding crash counts at the toll plazas where express ETC lanes were implemented. TABLE 3 summarizes similar information for other barrier toll plazas which do not have open road tolling.

### TABLE 2 Statistical Summary of MADT and Monthly Crash Counts (Mean ±SD)

<table>
<thead>
<tr>
<th>Index</th>
<th>Toll Plaza</th>
<th>Dataset 1: without ORT</th>
<th>Dataset 2: with ORT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Time Period</td>
<td>MADT (×1000)</td>
</tr>
<tr>
<td>16</td>
<td>Cape May NB</td>
<td>01/01-04/05</td>
<td>15.66 ± 6.20</td>
</tr>
<tr>
<td>17</td>
<td>Toms River NB</td>
<td>01/01-04/04</td>
<td>45.70 ± 6.75</td>
</tr>
<tr>
<td>18</td>
<td>Toms River SB</td>
<td>01/01-04/04</td>
<td>43.56 ± 6.27</td>
</tr>
<tr>
<td>19</td>
<td>Asbury Park NB</td>
<td>01/01-04/04</td>
<td>76.50 ± 9.72</td>
</tr>
<tr>
<td>20</td>
<td>Raritan SB</td>
<td>01/01-04/04</td>
<td>114.90 ± 12.59</td>
</tr>
<tr>
<td>21</td>
<td>Pasack Valley NB</td>
<td>01/01-12/02</td>
<td>41.35 ± 3.01</td>
</tr>
<tr>
<td>22</td>
<td>Pasack Valley SB</td>
<td>01/01-12/02</td>
<td>41.00 ± 2.70</td>
</tr>
</tbody>
</table>

### TABLE 3 MADT and Monthly Crash Counts for Other Barrier Toll Plazas (Mean ±SD)

<table>
<thead>
<tr>
<th>Index</th>
<th>Toll Plaza</th>
<th>Milepost</th>
<th>Available Time Period</th>
<th>MADT (×1000)</th>
<th>Crash</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Great Egg SB</td>
<td>28.8</td>
<td>01/01-12/09</td>
<td>20.66 ± 6.68</td>
<td>1.17 ± 1.36</td>
</tr>
<tr>
<td>2</td>
<td>New Gretna NB</td>
<td>53.5</td>
<td>01/01-12/09</td>
<td>22.71 ± 3.70</td>
<td>0.98 ± 0.98</td>
</tr>
<tr>
<td>3</td>
<td>Barnegat SB</td>
<td>68.9</td>
<td>01/01-12/09</td>
<td>34.60 ± 5.15</td>
<td>2.87 ± 2.14</td>
</tr>
<tr>
<td>4</td>
<td>Union NB</td>
<td>142.7</td>
<td>01/01-12/09</td>
<td>99.62 ± 6.32</td>
<td>12.18 ± 4.75</td>
</tr>
<tr>
<td>5</td>
<td>Essex SB</td>
<td>150.7</td>
<td>01/01-12/09</td>
<td>76.87 ± 4.79</td>
<td>7.72 ± 3.46</td>
</tr>
<tr>
<td>6</td>
<td>Bergen NB</td>
<td>160.5</td>
<td>01/01-12/09</td>
<td>70.02 ± 4.35</td>
<td>5.45 ± 2.43</td>
</tr>
<tr>
<td>7</td>
<td>Cape May SB</td>
<td>19.4</td>
<td>01/01-12/05</td>
<td>16.13 ± 6.44</td>
<td>0.57 ± 0.79</td>
</tr>
<tr>
<td>8</td>
<td>Great Egg NB</td>
<td>28.8</td>
<td>01/01-12/05</td>
<td>20.34 ± 6.74</td>
<td>0.72 ± 1.03</td>
</tr>
<tr>
<td>9</td>
<td>New Gretna SB</td>
<td>53.5</td>
<td>01/01-12/05</td>
<td>22.57 ± 3.74</td>
<td>1.37 ± 0.99</td>
</tr>
<tr>
<td>10</td>
<td>Barnegat NB</td>
<td>68.9</td>
<td>01/01-02/07</td>
<td>35.29 ± 5.31</td>
<td>2.09 ± 1.85</td>
</tr>
<tr>
<td>11</td>
<td>Asbury Park SB</td>
<td>104</td>
<td>01/01-08/04</td>
<td>76.95 ± 11.34</td>
<td>4.86 ± 2.43</td>
</tr>
<tr>
<td>12</td>
<td>Raritan NB</td>
<td>125.4</td>
<td>01/01-08/04</td>
<td>118.72 ± 13.33</td>
<td>11.32 ± 4.44</td>
</tr>
<tr>
<td>13</td>
<td>Union SB</td>
<td>142.7</td>
<td>01/01-02/05</td>
<td>102.80 ± 6.91</td>
<td>15.52 ± 5.24</td>
</tr>
<tr>
<td>14</td>
<td>Essex NB</td>
<td>150.7</td>
<td>01/01-06/05</td>
<td>82.29 ± 5.11</td>
<td>6.13 ± 2.61</td>
</tr>
<tr>
<td>15</td>
<td>Bergen SB</td>
<td>160.5</td>
<td>01/01-11/05</td>
<td>68.16 ± 4.20</td>
<td>4.27 ± 2.38</td>
</tr>
</tbody>
</table>
As seen from TABLE 2, the highest number of monthly crash counts is observed at the
Raritan SB toll plaza when the ORT was not deployed. Its traffic volume is the highest, as well.
After ORT was deployed, the mean crash frequency decreased by about 26.5 percent (from 8.23
per month to 6.05 per month). Crash reductions are also observed at both directions of Toms
River toll plazas and Pasack Valley southbound toll plaza despite of their increasing MADTs.
The remaining three sites seem to have higher crash risk after ORT systems were deployed.

However, the preliminary analysis in TABLE 2 cannot clarify the true effectiveness of
deploying express ETC lanes at the toll plazas on GSP because the change of crash frequencies
seems to be affected by the change in MADT. More importantly, this naïve before-after
comparison is subject to problems such as regression-to-the-mean, crash migration, maturation,
and external causal factors (e.g., 25-27). Thus, more rigorous evaluation methodologies are
needed to address the safety effects of the ORT systems at those toll plazas. Next section
presents the modeling and estimation methods used in this study.

Crash Modeling Using Poisson Mixture Models
To estimate the safety impacts of the ORT systems, the crash reduction rate (CRR) at the
ith toll plaza is calculated as follows:
\[
\text{CRR} = 1 - \frac{\text{Observed Crashes with ORT}}{\text{Expected Crashes without ORT}} = 1 - \frac{\sum_{t=1}^{N} Y_t}{\sum_{t=1}^{N} \theta_t}
\]
where \(Y_t\) is the observed crash frequency at the ith toll plaza in the ith time interval (month) after
the express ETC lanes were installed. \(\theta_t\) is the corresponding expected number of crashes at
the ith toll plaza in the ith month if the express ETC lanes have not been installed. \(N\) is the total
number of months after the express ETC lanes were deployed at the ith toll plaza.

To calculate CRR, the key step is to obtain the expected number of crashes \(\theta_t\) through
some analytical models. The Poisson regression model is a natural first choice for modeling the
longitudinal crash data because it can capture the more desirable statistical characteristics of
traffic crashes that are rare, random, nonnegative, discrete, and typically sporadic (28). However,
past research has indicated that the crash counts are likely to be over-dispersed (e.g., 29, 30). To
deal with the problems of over-dispersion, accounting for site-specific attributes and other
complex variations, etc, many extensions of simple Poisson models have been suggested. Two of
the frequently used alternatives are Poisson-Gamma (PG) mixture model and Poisson-Lognormal
(PL) mixture model. These models have the following model structures:

Assuming \(y_i\) denotes the number of independently observed crashes at a given site \(i\) in
the ith time interval. Assuming \(y_i\) follows the Poisson distribution with the mean of \(\theta_i\), we have
the basic Poisson regression model:
\[
y_i \sim \text{Poisson}(\theta_i) \quad (i = 1, 2, ..., n; \ t = 1, 2, ..., T)
\]
Let \(\mu_i\) describe the systematic variation of the expected number of crashes \(\theta_i\). \(\mu_i\) is
specified as a function of a set of explanatory variables. The commonly adopted function in crash
analysis is the log-linear model:
\[
\log(\mu_i) = X_i^T \beta
\]
where \(X_i\) is a vector of the explanatory variables such as geometric attributes, environment
conditions, etc. \(\beta\) is a \(k\) dimensional vector of unknown coefficients and \(\beta \sim \text{Normal}(0, \Sigma_\beta)\);
\(\Sigma_\beta\) is the \(k \times k\) dimensional variance-covariance vector and the non-diagonal elements are set to
zero \( \sigma_{\beta_i}^2 = 0, \forall i \neq j \) and diagonal elements are set to large positive values
(i.e., \( \sigma_{\beta_i}^2 = 1000, \forall i = 1, 2, \ldots, k \)).

To address issues of over-dispersion for unobserved heterogeneity, the noisy measurement \( \varepsilon_i \) is introduced into \( \theta_i \):

\[
\log(\theta_i) = \log(\mu_i) + \varepsilon_i \tag{4}
\]

\[
\theta_i = \mu_i \exp(\varepsilon_i) \tag{5}
\]

The term \( \exp(\varepsilon_i) \) in equation (5) denotes a multiplicative random effect (31). For Poisson-Gamma model, it usually assumes that \( \exp(\varepsilon_i) \) is independent and follows Gamma distribution for all sites \( i \) and \( t \). Similarly, Poisson-Lognormal model assumes that the noisy structure \( \exp(\varepsilon_i) \) is Lognormal distributed.

\[
\exp(\varepsilon_i) \sim \text{Gamma}(\alpha_i, \alpha_2) \quad \text{(PG model)} \tag{6}
\]

\[
\exp(\varepsilon_i) \sim \text{Lognormal}(0, \sigma_{\varepsilon_i}^2) \text{ or } \exp(\varepsilon_i) \sim \text{Normal}(0, \sigma_{\varepsilon_i}^2) \quad \text{(PL model)} \tag{7}
\]

where \( \alpha_i \) and \( \alpha_2 \) are the shape parameter and reciprocal of a scale parameter of Gamma distribution, respectively; the Gamma distribution has \( \text{mean} = \alpha_i / \alpha_2 \) and \( \text{variance} = \alpha_i / \alpha_2^2 \). By specifying \( \alpha_i = \alpha_2 = \varphi \), the Poisson–Gamma model becomes Negative-Binomial (NB) model; \( \varphi \) is the inverse dispersion parameter and \( \varphi > 0 \). \( \sigma_{\varepsilon_i}^2 \) denotes extra Poisson variance among observations.

Under the Poisson-Gamma (or NB) model, the expected number of crashes and its variance are:

\[
E(Y_i) = \theta_i = \mu_i = \exp(X_i' \beta) \tag{8}
\]

\[
\text{Var}(Y_i) = E(Y_i) + \text{Var}(E(Y_i))^2 / \varphi \tag{9}
\]

Similarly, the expected number of crashes and its variance under the Poisson-Lognormal model are follows:

\[
E(Y_i) = \theta_i = \mu_i \exp(\varepsilon_i) = \mu_i \exp(0.5 \sigma_{\varepsilon_i}^2) \tag{10}
\]

\[
\text{Var}(Y_i) = E(Y_i) + [E(Y_i)]^2 \{\exp(\sigma_{\varepsilon_i}^2) - 1\} \tag{11}
\]

The variance shown in equations (9) and (11) is always larger than the mean. Thus, these models are more appropriate for modeling the over-dispersed crash data.

Moreover, hierarchical Bayes version of the PG model and PL model can be obtained by imposing extra hyper-priors for the parameters to consider more stages of randomness. TABLE 4 summarizes the two model structures used in this study.

**TABLE 4 Hierarchical Bayes Models for Crash Frequency at the Toll Plazas on GSP**

<table>
<thead>
<tr>
<th>Poisson-Gamma</th>
<th>Poisson-Lognormal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_i = \mu_i \exp(\varepsilon_i) )</td>
<td>( \theta_i = \mu_i \exp(\varepsilon_i) )</td>
</tr>
<tr>
<td>( \exp(\varepsilon_i) \sim \text{Gamma}(\alpha_i, \alpha_2) )</td>
<td>( \exp(\varepsilon_i) \sim \text{Lognormal}(0, \sigma_{\varepsilon_i}^2) )</td>
</tr>
<tr>
<td>( \varphi \sim \text{Gamma}(\alpha_i, \alpha_2) )</td>
<td>( \sigma_{\varepsilon_i}^2 \sim \text{Gamma}(\alpha_1, \alpha_2) )</td>
</tr>
<tr>
<td>( \alpha_1 \sim \text{Exponential}(\alpha) )</td>
<td>( \alpha_1 \sim \text{Exponential}(\alpha) )</td>
</tr>
<tr>
<td>( \alpha_2 \sim \text{Gamma}(b, c) )</td>
<td>( \alpha_2 \sim \text{Gamma}(b, c) )</td>
</tr>
</tbody>
</table>

Data listed in TABLE 3 are combined with the dataset 1 in TABLE 2 to develop the link function of \( \mu_i \) and estimate the parameters. Specifically, the structure of the link function is shown in equation (12). The explanatory variables are summarized in TABLE 5.
log(μᵢ) = β₀ + β₁ × log(MADT) + β₂ × log(AL) + β₃ × log(DL) + β₄ × ACM + β₅ × CASH + β₆ × ETC + β₇ × S

TABLE 5 Model Covariates and Their Corresponding Statistical Summary

<table>
<thead>
<tr>
<th>Covariates</th>
<th>Symbol</th>
<th>Description</th>
<th>Mean ± SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of observed crashes</td>
<td>Y</td>
<td>Crashes per month</td>
<td>4.67 ± 4.86</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Monthly average daily traffic</td>
<td>MADT</td>
<td>Thousand vehicles per day</td>
<td>54.80 ±32.75</td>
<td>8.86</td>
<td>143.79</td>
</tr>
<tr>
<td>Length of approach zone</td>
<td>AL</td>
<td>Mile</td>
<td>0.21 ± 0.06</td>
<td>0.12</td>
<td>0.40</td>
</tr>
<tr>
<td>Length of departure zone</td>
<td>DL</td>
<td>Mile</td>
<td>0.21 ± 0.06</td>
<td>0.12</td>
<td>0.4</td>
</tr>
<tr>
<td>Number of ACM tollbooths</td>
<td>ACM</td>
<td>Tollbooths primarily use ACM</td>
<td>3.60 ± 1.41</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Number of cash tollbooths</td>
<td>CASH</td>
<td>Tollbooths primarily use cash</td>
<td>1.71 ± 0.75</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Number of regular ETC lanes</td>
<td>ETC</td>
<td>Tollbooths primarily use ETC</td>
<td>3.57 ± 2.08</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Season</td>
<td>S</td>
<td>Winter(Month=12,1,2), Spring(Month=3,4,5)</td>
<td>2.48 ± 1.12</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Summer(Month=6,7,8), Fall(Month=9,10,11)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Finally, the model parameters shown in TABLE 4 and the parameters of equation (12) are estimated in a Full Bayes context via Markov Chain Monte Carlo (MCMC) sampling in WinBUGS (32). The methodology has been widely used in road safety studies (e.g., 31, 33 & 34). Non-informative prior distributions are imposed on hyper-parameters in TABLE 4 to reflect the lack of prior information. Convergence of each model parameter is identified by monitoring MCMC trace plots and the Brooks-Gelman-Rubin (BGR) convergence statistic set in WinBUGS. Deviance Information Criterion (DIC) is used to compare different models (35, 36). To assess the accuracy of the posterior estimates for each parameter, the ratio of the Monte Carlo error relative to the standard deviation of each parameter is suggested to be less than 0.05 (37).

RESULTS & DISCUSSION

The posterior estimates of model parameters were obtained from the Full Bayes analysis based on 10,000 posterior samples via WinBUGS. The estimation results are summarized in TABLE 6. The convergence of each model parameter was verified as the BGR convergence statistics were below 1.2. The ratio of the Monte Carlo error relative to the standard deviation of each parameter is about 0.01 to 0.08. The two models were compared by computing the DIC as presented by Spiegelhalter et al. (35). The computed DIC statistics were 5674 and 5678 under the Poisson-Gamma model, Poisson-Lognormal model, respectively. As a rule of thumb, the smaller the DIC the better the model fit, and a difference larger than 10 suggests in favor of the model with smaller DIC. However, if the difference in DIC is less than 5, and the models make very different inferences, then it might be misleading to report the model with the lowest DIC (35, 36). Using the DIC values in TABLE 6, we see that the DIC difference in this study is less than 5. Thus, the results of both models are reported.
From TABLE 6 we note that all parameter estimates except $\beta_s$ are significantly different from zero as their 95-percent Bayesian credible intervals do not cover zero under both models. The estimates of $\varphi$ for Poisson-Gamma model and $\sigma^2$ for Poisson-Lognormal are significant, demonstrating the presence of over-dispersion in the crash data.

As shown in TABLE 6, crash occurrence rate is expected to increase with daily traffic. This result is consistent with the general finding in traffic safety studies as more vehicles are likely to cause more complex interactions among vehicles and therefore more crashes (31).

The length of the approach zone and the departure zone at a toll plaza can significantly influence the crash occurrence rate. Their corresponding coefficients $\beta_2$ and $\beta_3$ have negative signs indicating that the increase in length of these zones reduces crash likelihood. As expected, when the length of these sections increases, the total amount of conflicts between vehicles may be reduced because drivers have more time to make critical decisions (e.g., lane-changing and merging) at the toll plazas.

The positive coefficients of $\beta_4$ and $\beta_5$ indicate that the number of manual payment tollbooths is positively associated with the number of crashes at toll plazas. It can be attributed to the fact that more cash and coin tollbooths result in more stop-to-go traffic.

Similar to the findings reported in a previous study (38), the positive coefficient of $\beta_6$ suggests that the implementation of regular (low-speed) ETC system is also likely to increase the likelihood of the crash occurrence. An explanation for this is that drivers are more likely to be confused to locate appropriate lane for payment.

The variable $\beta_s$ which turned out to be statistically not significant suggests that there are no distinct seasonal differences in terms of toll plaza safety at these locations.

TABLE 7 presents the evaluation results in terms of crash reduction rate (CRR) for implementing ORT at the mainline toll plazas on Garden State Parkway. The estimated results under both models show a reduction in crash occurrence rate at most of the toll plazas after installing express ETC systems. The highest crash reduction rate is observed at Raritan SB toll plaza, where the estimated CRR is more than 40 percent. This toll plaza is the busiest one among other toll plazas. Before the deployment of express ETC lanes it used to have 20 tollbooths and
served more than 100,000 vehicles per day. Five express ETC lanes were added to allow vehicles with transponders (e.g., E-ZPass tags) to travel at 55 mph. This is the largest ORT system on the Garden State Parkway. The decrease among Toms River and Pascack Valley toll plazas ranges from 17 percent to 36 percent. The composite results are also provided in TABLE 7. Overall, motor vehicle crashes are decreased by about 24 percent at the toll plazas with a standard deviation of 2.4 percent. The overall results support the findings of a previous study (1) that ORT can cause a significant reduction in the number of crashes.

### TABLE 7 Estimates of Crash Reduction Rates for Implementing ORT at Toll Plazas

<table>
<thead>
<tr>
<th>Toll Plaza</th>
<th>Observed Crashes with ORT</th>
<th>Poisson-Gamma</th>
<th>Poisson-Lognormal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated Crashes</td>
<td></td>
<td>Estimated Crashes</td>
</tr>
<tr>
<td></td>
<td>without ORT</td>
<td>CRR (95% CI)</td>
<td>without ORT</td>
</tr>
<tr>
<td>Cape May NB</td>
<td>38</td>
<td>-0.759 (-1.049,-0.499)</td>
<td>21</td>
</tr>
<tr>
<td>Toms River NB</td>
<td>118</td>
<td>0.358 (0.283,0.427)</td>
<td>186</td>
</tr>
<tr>
<td>Toms River SB</td>
<td>131</td>
<td>0.343 (0.274,0.406)</td>
<td>200</td>
</tr>
<tr>
<td>Asbury Park NB</td>
<td>402</td>
<td>-0.031 (-0.199,0.121)</td>
<td>386</td>
</tr>
<tr>
<td>Raritan SB</td>
<td>339</td>
<td>0.404 (0.322,0.474)</td>
<td>568</td>
</tr>
<tr>
<td>Pascack Valley NB</td>
<td>79</td>
<td>0.303 (0.222,0.385)</td>
<td>115</td>
</tr>
<tr>
<td>Pascack Valley SB</td>
<td>98</td>
<td>0.174 (0.080,0.275)</td>
<td>120</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td>1205</td>
<td>0.247 (0.198,0.294)</td>
<td>1596</td>
</tr>
</tbody>
</table>

Despite the overall reduction, it should be noted that the number of crashes is observed to have increased after the implementation of the ORT systems at Cape May NB and Asbury Park NB toll plazas. The estimated results under both models suggest that the number of crashes at Asbury Park NB toll Plaza increased about 3-4 percent after three express ETC lanes were added. Whereas this small number of increase does not suggest a clear impact of the ORT system as its 95-percent credible interval covers zero. Cape May NB toll plaza has the lowest number of crash counts among all toll plazas. However, it shows more than 70 percent increase of crash frequency after the ORT system was installed at this toll plaza.

A more careful review of the reported crashes at these two toll plaza was conducted. FIGURE 3 shows the spatial distribution of the reported crashes before and after the ORT system was deployed. As seen from FIGURE 3a and FIGURE 3c, more than 40 percent of crashes occurred at the approach section of the tollbooths during 2001 to 2004 when the ORT system was not installed yet. Most of these crashes are rear end, side swipe and fixed object collisions. In contrast, FIGURE 3b and FIGURE 3d illustrate the observed crashes during 2006 to 2009 after the ORT system was in operation. Interestingly, only about 10 to 20 percent of crashes occurred at the immediate vicinity of the tollbooths at both toll plazas. Notably, more crashes occurred at the sections before the ORT signs (FIGURE 3b) and the merge section (FIGURE 3d). The major crash types are found to be rear end, side swipe and fixed object collisions at these sections. As a comparison, we also reviewed the reported crashes at other toll plazas that have significant crash reductions after the ORT system was implemented. FIGURE 4 shows an example of the crash distributions of the Raritan SB toll plaza. The crash distributions at this toll plaza did not vary significantly before and after the implementation of the ORT system. No obvious changes in crash frequencies were found around diverge and merge sections.

Vehicles have to make a decision whether to use the express lanes or to divert to barrier tollbooths when approaching the ORT signs. After leaving the barrier tollbooths, the slow moving vehicles have to merge with the high-speed vehicles coming from the express ETC lanes, which might lead to higher number of traffic conflicts. FIGURE 3 and FIGURE 4 suggest that
when retrofitting an existing toll plaza to add ORT system, attention should be paid to factors such as signage, diversion and merge designs.

FIGURE 3 Crash distributions at Cape May NB & Asbury Park NB toll plazas

FIGURE 4 Crash distributions at Raritan SB toll plaza before and after deploying ORT

CONCLUSIONS
This study aims to evaluate the impact of the open road tolling (ORT) on safety performance of the mainline toll plazas. Garden State Parkway (GSP) in New Jersey was used as the case study. Seven toll plazas where the ORT systems were deployed were used in the analysis. Crash data, related traffic data and toll plaza configurations between 2001 and 2009 were used to support the analysis. Crash modeling based on Full Bayes methodology was conducted to determine the crash reduction rate (CRR) of the ORT system.

The safety performance functions developed via Full Bayes methodology show that the number of crashes increase with daily traffic volume and the number of barrier tollbooths. The results also suggest that the number of regular (low-speed) ETC toll lanes might also lead to increased likelihood of crash occurrence just as cash and ACM toll lanes do. An explanation for this is that drivers are more likely to be confused when selecting appropriate toll lane. On the other hand, increasing the length of toll plaza arrival and departure zones is likely to reduce the number of crashes. As expected, when the length of these zones increases, the total amount of conflicts between vehicles may reduce because drivers have more time to make critical decisions (e.g., lane-change and merge) along approach and departure sections.

The safety evaluations show that the overall crash frequency at the toll plazas on GSP was reduced by a crash reduction rate (CRR) of 24 percent after the deployment of ORT system at toll plazas. The hypothesis that the ORT with express ETC lanes reduces the crash rates at toll plazas on GSP and positively impacts the safety is supported by the analysis results. Individually, five of the toll plazas show a decrease in crash occurrence rate, with a reduction rate ranging from 17 to 40 percent. Raritan SB toll plaza had the highest reduction of 40 percent. In contrast, crash model estimated that the other two toll plazas Cape May NB and Asbury Park NB have more number of crashes after the deployment of ORT. A detailed review of the crash occurred along these two toll plazas was conducted. The results suggest that less crashes occurred at the immediate vicinity of the tollbooths at both toll plazas after the ORT systems were installed, whereas high number of crashes are likely to occur at the diversion and merging sections. As vehicles without transponders (e.g., E-ZPass tags) have to leave the mainline to use barrier tollbooths and then merge back, lane changes and speed differential among vehicles increase at these sections. This increase may be the reason of the higher likelihood of rear end and side swipe collisions observed in the crash data. However, more research is needed for better understanding this assumption.

The analyses results indicate that the implementation of the ORT system improved safety on most of the toll plazas on GSP. In addition, when deploying ORT systems, special attention should be paid to some critical components such as signage guidance, diversion and merge designs.

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REFERENCES


