Effect of Removing Freeway Mainline Barrier Toll Plazas on Safety

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ABSTRACT
Toll plaza safety is a critical issue. Toll plazas induce motor vehicle crashes and also put workers such as toll collectors at risk. Therefore, enhancing safety at a toll plaza is crucial to improving safety on tolled roadways. This study aims to evaluate the safety effect of removing mainline barrier toll plazas on highways using Empirical Bayesian (EB) methodology. Recent removals of barrier toll plaza on the Garden State Parkway in New Jersey were used as a case study. Multiple-year traffic and crash data before and after the removals of the barrier toll plazas were used for analysis. Toll plaza crash frequency models as a function of traffic flow and other factors were developed, with the modeling results suggesting that there is a nonlinear relationship between toll plaza crash occurrences and both traffic flow as well as toll booth configurations. The EB approach is also used to predict crash frequency assuming that the barrier toll booths were not removed. These EB-based estimates were compared with the observed number of crashes after the removals of the toll plazas. Individual comparisons show reductions in crash frequency at almost all of the toll plazas and an estimated reduction of 47.2 percent overall at all toll plazas due to the removal of the barrier toll booths. The estimated crash cost was reduced by 43.2 percent. These estimated reductions demonstrate that the removal of barrier toll plazas is a very beneficial step towards improving safety of toll roads.
INTRODUCTION

Highway authorities have continued to use advanced technologies to improve efficiency at toll plazas. A first step was the use of automatic coin machines (ACM), and later was the establishment of electronic toll collection (ETC) systems. ETC enables non-stop toll charges via electronic transponders or other forms of automatic vehicle identification (AVI). ETC is widely recognized as a successful Intelligent Transportation Systems (ITS) application with numerous benefits such as lower transaction time, improved throughput, and reduced air pollution and fuel consumption (e.g., 1-4). However, ETC systems on traditional barrier toll plazas still require vehicles to slow down into channeled toll lanes, which itself requires vehicles to make complex lane-choice decisions at relatively high speeds. Therefore, safety issues at barrier toll plazas still exist despite increased throughput.

As stated in Brown et al. (5), even though toll plazas have been designed and constructed in the United States for more than 50 years, there are no widely accepted design standards for toll plaza uniformity or safety, with the only standards developed by individual toll operators based on their experience (6-10). It is stated that there has been an increase in the number of toll roadways being built with little information on how such barrier toll plazas affect crash rates (11). Similarly in Abdelwahab et al. (12), the urgent need to study traffic safety issues of toll plazas is emphasized.

Removing existing toll plazas can be deemed safer as they eliminate complicate lane-choice decisions as well as the barrier itself as an obstruction, which both increase the likelihood of crashes. However, unlike easily measurable benefits such as reduction of transaction-related delays and pollution, it is difficult to evaluate safety performance of removing the barrier toll plazas after a short period of time. Few studies have briefly analyzed the safety problems created by the presence of toll plazas (13-15).

The main objective of this study is twofold:
(1) Model the crash occurrence at barrier toll plazas, and
(2) Evaluate the safety effects of removing the barrier plazas on toll roads.

The removals of mainline barrier toll plazas on the Garden State Parkway in New Jersey are used as a case study. Crash models are developed to investigate the safety performance before and after the removals of the mainline toll booths. The crash data available in this study cover the period from 2001 to 2010. Therefore, safety performance of removing the barrier toll plazas can be analyzed and compared using the multi-year crash data (16).

REMOVAL OF MAINLINE TOLL PLAZAS ON FREEWAYS

The Gardens State Parkway (GSP), a 172.4-mile limited-access tolled parkway with 359 exits and entrances, is used as the case study to analyze the impacts of the removals of toll plazas on freeways. The main reasons for selecting GSP as the case study are (1) GSP is a major and heavily congested limited access highway; (2) 10 barrier toll plazas on the mainline have been removed since 2001; and (3) Before and after crash data for GSP is available on-line (16) from the New Jersey Department of Transportation (NJDOT). 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 entrance and exit ramps (17). It is among America’s busiest highways, serving users from NJ and NY’s most marketable communities (18, 19).

A traditional low-speed ETC system was deployed on GSP in 1999. The entire system was completed in August 2000 (19). The system has been widely adopted by travelers with an ETC penetration rate beyond 70 percent (20).

In 2001, the state government issued an order to promote a ten-year congestion relief plan for GSP (21). Under the plan, elimination of mainline barrier toll plazas in one direction and use of express ETC lanes of open road tolling (ORT) in the other direction were recommended. By 2010, all mainline barrier toll plazas but one were converted to one-way tolling (express ETC lanes were added to both directions at the Toms River toll plaza). TABLE 1 summarizes the toll plaza removal date of each barrier toll plaza. FIGURE 1 shows an example of the progression of removing toll collection at the Pascack Valley northbound toll plaza. The original toll plaza [see FIGURE 1 (a)] was retrofitted to add two express ETC lanes in each direction in 2004, shown in FIGURE 1 (b). Its remaining barrier toll booths
were removed in 2010 and the toll plaza becomes a standard roadway section without any toll collection [see FIGURE 1 (c)]. Similar conversions were conducted at the other nine toll plazas in TABLE 1.

<table>
<thead>
<tr>
<th>Toll Plaza</th>
<th>Milepost</th>
<th>Removal Date</th>
<th>Removed Toll booths</th>
<th>Current Lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape May SB</td>
<td>19.4</td>
<td>1/8/2006</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Great Egg NB</td>
<td>28.8</td>
<td>1/8/2006</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>New Gretna SB</td>
<td>53.5</td>
<td>1/8/2006</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Barnegat NB</td>
<td>68.9</td>
<td>3/10/2007</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Asbury Park SB</td>
<td>104</td>
<td>9/12/2004</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Raritan NB</td>
<td>125.4</td>
<td>9/12/2004</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>Union SB</td>
<td>142.7</td>
<td>3/6/2005</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>Essex NB</td>
<td>150.7</td>
<td>7/17/2005</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Bergen SB</td>
<td>160.5</td>
<td>12/4/2005</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Pascack Valley NB</td>
<td>166.1</td>
<td>2/20/2010</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

Removing those traditional barrier toll booths that have served more than fifty years on GSP conceivably eliminates bottlenecks on the freeway. It can improve the highway capacity and reduce emissions related to the heavy stop-and-go traffic at barrier toll booths. By realigning the plaza roadway to allow for smooth traveling, it is deemed to avoid the safety pitfalls of conventional toll plazas. However, the safety benefits of removing the barrier toll plazas have not yet been quantified.
SAFETY IMPACT ANALYSIS

Data Description

Several data were collected to investigate crash characteristics at the mainline toll plazas. The crash records for toll plazas are obtained from the raw crash database of the New Jersey Department of Transportation (NJDOT) (16). The records provide detailed information on each crash such as the time, location, collision type, and severity. 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 impact area is assumed to be one mile, which covers 0.5 mile before and after the toll booths, respectively. Crashes that occurred within the impact area of each toll plaza were extracted from the raw crash records. Data in the year when the toll plaza was removed were excluded for analysis. In addition, the most recently removed toll plaza, Pascack Valley NB toll plaza listed in TABLE 1, was also excluded for analysis. TABLE 2 presents the average number of crashes observed in each year before and after the mainline barrier toll plazas were removed.

<table>
<thead>
<tr>
<th>Toll Plaza</th>
<th>With Toll Plaza (Annual Observed Crashes)</th>
<th>Without Toll Plaza (Annual Observed Crashes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Period</td>
<td>All</td>
</tr>
<tr>
<td>Cape May SB</td>
<td>2001-2005</td>
<td>6.8</td>
</tr>
<tr>
<td>Great Egg NB</td>
<td>2001-2005</td>
<td>8.2</td>
</tr>
<tr>
<td>New Gretna SB</td>
<td>2001-2005</td>
<td>15.2</td>
</tr>
<tr>
<td>Barnegat NB</td>
<td>2001-2006</td>
<td>22.3</td>
</tr>
<tr>
<td>Asbury Park SB</td>
<td>2001-2003</td>
<td>52.3</td>
</tr>
<tr>
<td>Raritan NB</td>
<td>2001-2003</td>
<td>129.0</td>
</tr>
<tr>
<td>Union SB</td>
<td>2001-2004</td>
<td>182.3</td>
</tr>
<tr>
<td>Essex NB</td>
<td>2001-2004</td>
<td>67.5</td>
</tr>
<tr>
<td>Bergen SB</td>
<td>2001-2004</td>
<td>46.8</td>
</tr>
</tbody>
</table>

The crash counts shown in TABLE 2 indicate that the crash counts at some toll plazas such as Cape May SB were reduced whereas others such as Bergen SB were increased. However, the observed crash counts before and after the removals of toll plazas should not be directly compared as many casual factors have not been addressed. The GSP toll plaza configurations and annual average daily traffic (AADT) data for the toll plazas between 2001 and 2010 were obtained from the New Jersey Turnpike Authority (NJTA).

Empirical Bayesian Analysis

Safety assessment is a challenging task. Intuitively, safety effect/impact can be determined like previous studies (25,26) by simply comparing the historical crash frequencies or rates before and after the implementation of treatments at toll plazas: \( \delta = A - B \) or \( \theta = A/B \), where \( B \) is the reported crash frequency or rate in the before period; \( A \) is the reported crash frequency or rate in the after period; \( \delta \) is the change of crash frequency or rate; and \( \theta \) is the index of effectiveness. However, such simple analysis is often unable to clarify the actual effectiveness of the treatment because of the natural change in safety over time. In addition, it is undesirable to predict the index of effectiveness by merely using the observed number of crashes as it does not account for the potential change in traffic volume. Besides, such a simple before-after comparison cannot account for many issues such as regression-to-the-mean effect as well as changes in other casual factors (27,28,29). Therefore better evaluation approaches are necessary to assess the safety effect of the removing the mainline toll plazas.
The methodology adopted herein is the Empirical Bayesian (EB) method. The EB method pioneered by Hauer (27) has been widely recognized as a very effective tool for various observational before-after traffic safety studies (24,30-34). Instead of merely using observed crash counts or rates $B$ in the before period, the essential idea of EB procedure estimates the long-term safety of an entity using two different sets of evidence, that is, the historical crash data of the entity and the predicted number of crashes obtained from a safety performance function (SPF) for similar sites (24,35). Compared to other simple before-after evaluation methods, the EB method has some distinct advantages. First and foremost, the EB method offers improved estimates of the expected number of crashes $\pi$ had the treatment not been implemented in the after period by accounting for the regression-to-the-mean effect along with changes in traffic volume and other factors (32,36). In addition, it is preferred as the need of a comparison group is not compulsory (36,37,38). For before-after methods relying on a comparison group, it may be difficult to obtain and appropriately select the comparison group, as discussed in (39,40).

The detailed EB procedure is not described in this study, but is well documented in literature (e.g.,27,36,37,41). Only the overall index of effectiveness, its variance, and standard error for the removals of the toll plazas are presented as follows:

$$\theta = \frac{\pi_a}{[1+\text{Var}(\pi_a)/\pi_a^2]}$$

(1)

$$\text{Var}(\theta) = \theta^2 \times \frac{1/\pi_a + \text{Var}(\pi_a)/\pi_a^2}{[1+\text{Var}(\pi_a)/\pi_a^2]^2}$$

(2)

$$S.E.(\theta) = \sqrt{\text{Var}(\theta)}$$

(3)

where $\theta$ is the overall index of effectiveness; $\pi_a$ is the expected toll number of crashes based on EB approach had the toll plazas not been removed; $\pi_a$ is the total number of crashes observed after the toll plazas were removed; $\text{Var}(\theta)$ represents variance and $S.E.(\theta)$ represents standard error of $\theta$.

The overall safety effectiveness as a percentage change of crash frequency across all removed toll plazas is $100(1-\theta)$. The 95 percent confidence interval (CI) for $\theta$ is estimated as $\theta \pm 1.96S.E.(\theta)$. If $\theta < 1$ and its confidence interval does not contain 1, then the result implies that the removals of the toll plazas have significantly improved the safety (in terms of crash reduction). In contrast, if $\theta > 1$ and the lower limit of the confidence interval is greater than 1, then the removals of the toll plazas have a negative impact on toll plaza safety (in terms of crash increase). Otherwise, the removals of the toll plazas have no obvious impact on the safety performance of the toll plaza sections.

Data from thirteen other mainline toll plazas on GSP that have not been removed between 2001 and 2010 were used to develop the SPF. Specifically, negative binomial (NB) regression models for total crashes, PDO crashes, and injury crashes (combined fatal crashes) were developed to link a set of explanatory variables with crash counts at the toll plazas. The quantifiable variables considered in this study are summarized in TABLE 3. It should be noted that some other variables such as roadway grade, traffic composition and weather conditions may also affect the safety performance of the section. Therefore, if data were available, these variables should be considered in the model. The final safety SPF for predicting the number of crashes at toll plaza can be specified as follows:

$$\ln(\lambda_i) = \beta_0 + \ln(AADT_i)^{\beta_1} + \ln(A\text{Zone}_i)^{\beta_2} + \beta_3\ln(D\text{Zone}_i) + \beta_4\text{Booth}_i + \beta_5\text{ACM}_i + \beta_6\text{CASH}_i + \beta_7\text{ETC}_i + \beta_8\text{Year}_i$$

(4)

where $\lambda_i$ is the predicted number of crashes at $i^{th}$ toll plaza; $\beta_0$ is a constant and $\beta_j$ ($j=1,2,...,8$) represents the coefficient of each explanatory variable.
TABLE 3 Variables Considered for the Safety Performance Functions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of crashes</td>
<td>Y</td>
<td>Annual crashes at a toll plaza (dependent variable)</td>
</tr>
<tr>
<td>Flow</td>
<td>AADT</td>
<td>Traffic flow (vehicles) per day per toll booth</td>
</tr>
<tr>
<td>Length of approach zone</td>
<td>Azone</td>
<td>Length of approach zone of a toll plaza (mile)</td>
</tr>
<tr>
<td>Length of departure zone</td>
<td>Dzone</td>
<td>Length of departure zone of a toll plaza (mile)</td>
</tr>
<tr>
<td>Number of toll booths</td>
<td>Booth</td>
<td>Total number of toll booths at a toll plaza</td>
</tr>
<tr>
<td>Proportion of exact change toll booths</td>
<td>ACM</td>
<td>Proportion of toll booths that primarily use exact change</td>
</tr>
<tr>
<td>Proportion of cash toll booths</td>
<td>CASH</td>
<td>Proportion of toll booths that primarily use cash</td>
</tr>
<tr>
<td>Proportion of express ETC lanes</td>
<td>ExETC</td>
<td>Proportion of toll booths that primarily use high-speed ETC</td>
</tr>
<tr>
<td>Year</td>
<td>Year</td>
<td>Order of year in study period to address time trend</td>
</tr>
</tbody>
</table>

RESULTS & DISCUSSION

The negative binomial (NB) regression models for toll plaza safety analysis were developed by crash categories, with the estimated model parameters presented in TABLE 4.

The results show that toll plaza crash frequency is expected to increase with traffic volume. This result is consistent with the common argument in traffic safety studies that more vehicles are likely to cause more unsafe interactions and therefore more crashes (32,42). The length of the approach zone is negatively associated with crash risk. In other words, the crashes can be reduced if a longer approach zone is available. This may be attributable to the fact that the longer approach zone provides more time to safely change lanes and select toll booths. Similarly, the length of the departure zone is also negatively associated with crash occurrence. The more toll booths a toll plaza has, the more crashes are expected to occur. The positive signs of the proportion of low speed toll booths (using cash and exact change payment) indicate that these toll booths were all positively associated with the number of crashes at toll plazas. This is expected as vehicles must slow down and pay tolls with cash at these toll booths. It causes more stop-and-go traffic which in turn increases the crash risk. More importantly, the crash counts will reduce if the proportion of express toll lanes is larger. This is consistent with our previous findings in (43) that the use of high-speed toll lanes (or open road tolling) will significantly reduce the number of crashes.

In addition, there was no obvious time trend of crash frequency at the toll plazas. These SPFs are then used to conduct EB estimation of crashes at the removed toll plazas listed in TABLE 2.

TABLE 4 Estimates of Coefficients for Safety Performance Functions

<table>
<thead>
<tr>
<th>NB Model</th>
<th>Total Crashes</th>
<th>PDO Crashes</th>
<th>Injury Crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>Coef.</td>
<td>Std.Err</td>
<td>P&gt;</td>
</tr>
<tr>
<td>log(AADT)</td>
<td>1.768</td>
<td>0.132</td>
<td>0.000</td>
</tr>
<tr>
<td>log(Azone)</td>
<td>-0.728</td>
<td>0.157</td>
<td>0.000</td>
</tr>
<tr>
<td>log(Dzone)</td>
<td>-0.509</td>
<td>0.157</td>
<td>0.001</td>
</tr>
<tr>
<td>Booth</td>
<td>0.174</td>
<td>0.013</td>
<td>0.000</td>
</tr>
<tr>
<td>Cash</td>
<td>0.746</td>
<td>0.613</td>
<td>0.223</td>
</tr>
<tr>
<td>ACM</td>
<td>0.789</td>
<td>0.492</td>
<td>0.109</td>
</tr>
<tr>
<td>ExETC</td>
<td>-1.044</td>
<td>0.344</td>
<td>0.002</td>
</tr>
<tr>
<td>Year</td>
<td>0.017</td>
<td>0.015</td>
<td>0.245</td>
</tr>
<tr>
<td>Constant</td>
<td>-15.628</td>
<td>1.222</td>
<td>0.000</td>
</tr>
<tr>
<td>Dispersion</td>
<td>0.083</td>
<td>0.015</td>
<td>---</td>
</tr>
</tbody>
</table>
TABLE 5 presents the results of the Empirical Bayesian (EB) before-after evaluation of removing mainline barrier toll plazas on Garden State Parkway. The total number of observed crashes during the period without the barrier toll plazas is compared with the number of crashes predicted had the toll plazas not been removed. The results show that almost all toll plazas have a significant estimated reduction in crash frequency after the toll plazas have been removed. The index of effectiveness $\theta$ for Barnegat NB toll plaza as well as Bergen SB toll plaza is relatively larger than the others. This indicates that the toll plaza removals at these two sites were less effective than other sites. Detailed crash characteristics should be examined to reveal the reasons why the projects at these two sites were less effective. The overall index of effectiveness $\theta$ for total crashes is 0.528 which implies a crash reduction factor of $100(1 - \theta) = 47.2$ percent. Similarly, the overall crash reduction factors for PDO crashes and injury crashes are 49.0 percent and 40.3 percent, respectively.

<table>
<thead>
<tr>
<th>Toll Plaza</th>
<th>Without Toll Plaza (observed)</th>
<th>With Toll Plaza (EB predicted)</th>
<th>Index of Effectiveness($\theta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>PDO</td>
<td>Injury</td>
</tr>
<tr>
<td>Cape May SB</td>
<td>12</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Great Egg NB</td>
<td>24</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>New Gretna NB</td>
<td>21</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>Barnegat NB</td>
<td>70</td>
<td>46</td>
<td>24</td>
</tr>
<tr>
<td>Asbury Park SB</td>
<td>150</td>
<td>118</td>
<td>32</td>
</tr>
<tr>
<td>Raritan NB</td>
<td>395</td>
<td>310</td>
<td>85</td>
</tr>
<tr>
<td>Union SB</td>
<td>654</td>
<td>509</td>
<td>145</td>
</tr>
<tr>
<td>Essex NB</td>
<td>176</td>
<td>126</td>
<td>50</td>
</tr>
<tr>
<td>Bergen SB</td>
<td>241</td>
<td>199</td>
<td>42</td>
</tr>
<tr>
<td>All Toll Plazas</td>
<td>1743</td>
<td>1350</td>
<td>393</td>
</tr>
</tbody>
</table>

Notes: (1) EB estimate is the expected number of crashes during after period had the toll plaza not been deployed; (2) $\theta$ is estimated index of effectiveness; and (3) Statistically significant $\theta$ is shown in blue number.

To examine the economic impact of removing the barrier toll plazas in terms of safety cost, benefit cost analysis is conducted. The average economic cost per crash ($8,900 for a PDO crash and $70,200 for an injury crash) estimated by the National Safety Council is used for the analysis (44). The benefit is estimated by production of crash cost with the number of reductions in PDO and injury crashes. If the toll plazas were not removed, the estimated total crash cost is approximately $69.7 million during the after period. In contrast, the estimated crash cost after the removals of the toll plazas is estimated at only $39.6 million in total. Thus the overall crash cost reduction due to the removals of the barrier toll plazas is estimated at 43.2 percent.

CONCLUSIONS
This study aimed to evaluate the safety effects of removing mainline barrier toll plazas on tolled roadways. The removal of nine barrier toll plazas on the Garden State Parkway (GSP) in New Jersey between 2001 and 2010 was used as the case study. Crash data, related traffic volume data, and lane configurations for each toll plaza were collected to support the analysis. Crash modeling based on the Empirical Bayesian (EB) method was conducted to determine the index of effectiveness of removing the toll plazas. Results of the before-and-after comparisons show that the removals of these toll plazas significantly improved the safety at these locations. The estimated results show that the overall crash occurrence at these toll plazas was reduced by 47.2 percent after the removals of barrier toll plazas. The
estimated crash cost was reduced by 43.2 percent. The negative safety impacts of the barrier toll plazas are identified as the mixed use of different toll booths at barrier toll plazas, which force drivers to make more lane changes and travel at varying speeds at toll plazas. Frequent lane changes and large speed variations in turn increase the likelihood of crash at these locations. It is thus concluded that the removals of traditional barrier toll plazas can be a beneficial step towards significantly improving safety on the toll roads.

Though the analyses focused on removing barrier toll plazas, the findings could be useful to support some other treatments to enhance safety at toll plazas. For instance, if it is impossible to remove a toll plaza, new tolling solutions like open road tolling (ORT) system can be used. Once toll booths are converted to ORT lanes, the tolling function can be kept but the impact on traffic as well as safety can be reduced because there would be no physical barrier toll booths to impede traffic.

DISCLAIMER
The contents of this paper reflect views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents of the paper do not necessarily reflect the official views or policies of any agencies.

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