Safety Evaluation of Hybrid Main-Line Toll Plazas

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Traditional main-line toll plazas on expressways may have both safety and operational challenges. Although many studies have demonstrated the operational and environmental impacts of conversion from traditional toll plazas to a barrier-free system (open road tolling), research that quantifies the safety benefits of new tolling systems is lacking. This study evaluated the safety effectiveness of the conversion from a traditional main-line toll plaza design to a hybrid main-line toll plaza (HMTP) system. An HMTP system combines both open road tolling on the main line and separate traditional toll collection to the side. Various observational before–after studies were applied on 98 main-line toll plazas (two directions) located on approximately 750 mi of toll roads in Florida; 30 of these were upgraded to the HMTP system. The multivariate empirical Bayes method produced the best crash modification factors with low standard errors, and its results indicated that the conversion from traditional main-line toll plaza to HMTP showed an average crash reduction of 47%, 46%, and 54% for total crashes, fatal and injury crashes, and property-damage-only crashes, respectively. The use of an HMTP system also significantly reduced rear-end crashes and lane-change–related crashes by an average of 65% and 55%, respectively. The use of the HMTP system was proved to be an excellent solution to several traffic operations, environmental, and economic problems. The results of this study proved that the safety effectiveness was significantly improved across all locations that were upgraded to an HMTP system.

Toll roads play a pivotal role in meeting U.S. transportation needs. The use of toll road systems has risen dramatically in the United States in recent years. In Florida, toll roads have almost doubled in number since 2000. Although toll roads offer a high level of service and well-maintained roadways, traditional toll facilities may pose great risks to drivers and workers. Traditional toll plaza systems require vehicles to rapidly decelerate, navigate through fare transaction options, and then accelerate and merge with traffic. These confusing maneuvers constitute safety challenges and form hazardous locations (hot spots) on toll roadways.

To counter these safety and operational challenges, toll road authorities are moving to the use of open road tolling (ORT) systems. The new barrier-free system depends on electronic toll collection (ETC), which uses electronic transponders or license plate recognition technology in an open road environment. This system allows drivers to travel at full speed with fewer diverge and merge maneuvers. An ORT can be implemented as one of two main types: (*a*) a completely barrier-free system that replaces all tollbooths with express ETC lanes and (*b*) a hybrid main-line toll plaza (HMTP) that retrofits existing tollbooths with express open ETC lanes (*1*–*6*). The second type is widely deployed by many toll authorities in Florida, Illinois, New Jersey, and elsewhere (*7*–*10*).

An HMTP was found to effectively address traffic operation, environmental, economic, and traffic safety challenges; Yang et al. found that the safety effect of removing main-line barrier toll plazas reduced the crash frequency by 47.2% and the crash cost by 43.2% (*10*). Klodzinski et al. concluded that the addition of an ORT to a main-line toll plaza in Florida reduced delays by almost 50% for cash users and about 55% for automatic coin machine users (*3*). A study by Levinson and Odlyzko found that the throughput of manual collection lanes can be increased from 350 to 400 vehicles per hour per lane up to 2,200 after an upgrade to express ETC lanes (*11*). The conversion from a traditional toll system to an HMTP system also was proved to significantly reduce emissions (*12*).

In 1995, the Orlando–Orange County Expressway Authority (OOCEA) implemented an ETC system at the existing main-line and ramp toll facilities. As of January 2009, OOCEA has converted most traditional toll plazas into hybrid toll plazas and has used HMTP design for all new contracted plazas since 2003 (*13*).

Although many studies have demonstrated the operational and environmental benefits of the conversion from traditional toll plazas to a barrier-free system (ORT), research that quantifies the safety impact of new tolling systems is lacking. Using 3.5 years of crash data, Mohamed et al. found that about 32% of the total crashes that occurred on an expressway system were located at the main-line toll plazas (*1*). Evaluating the safety effectiveness of how crash frequency and crash types or severity have changed because of the conversion of traditional toll plazas to hybrid toll plazas is one of the defined objectives in the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users.

This study evaluates the impact of the conversion of the traditional main-line toll plaza to an HMTP on crash frequency, crash types, and crash severity by using extensive data collected at multiple locations. The remainder of this paper consists of a description of the statistical methodology and data preparation and detailed results and discussions, followed by conclusions and recommendations.

METHODOLOGY

Three approaches were used for an observational before–after study: (*a*) naive before–after study (for illustration only), (*b*) before–after study with comparison group, and (*c*) before–after study with the empirical Bayes method. (The last two approaches are more reliable.)

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Naive Before–After Study

The naive before–after approach is the simplest method. Crash counts in the before period are used to predict the expected crash rate and, consequently, the expected crashes had the treatment not been implemented. This basic naive approach assumes that there was no change from the before to the after period that affected the safety of the entity under scrutiny; it is unable to account for the passage of time and its effect on other factors such as exposure, maturation, trend, and regression-to-the-mean bias.

Before–After Study with Comparison Group

To account for the influence of a variety of external causal factors that change with time, a before–after study with comparison group can be adopted. A comparison group is a group of control sites that remained untreated and that are similar to the treated sites for trends of crash history, traffic, geometric, and geographic characteristics. The crash data of the comparison group are used to estimate the crashes that would have occurred at the treated entities in the after period had the treatment not been applied. This method can provide more accurate estimates of the safety effect than a naive before–after study, particularly if the similarity between treated and comparison sites is high. The before–after study with comparison group method is based on two main assumptions (*14–17*):

1. The factors that affect safety have changed in the same manner from the before period to the after period in both treatment and comparison groups.
2. These changes in the various factors affect the safety of treatment and comparison groups in the same way.

From these assumptions, it can be supposed that the change in the number of crashes from the before period to the after period at the treated sites, in the case in which no countermeasures had been implemented, would have been in the same proportion as that for the comparison group. Accordingly, the expected number of crashes for the treated sites that would have occurred in the after period had no improvement been applied ($N_{\text{expected},T,A}$) follows (*14*):

$$N_{\text{expected},T,A} = N_{\text{observed},T,B} \times \frac{N_{\text{observed},C,A}}{N_{\text{observed},C,B}} \tag{1}$$

If the similarity between the comparison and the treated sites in the yearly crash trends is ideal, the variance of $N_{\text{expected},T,A}$ can be estimated with Equation 2:

$$\text{var}\left(N_{\text{expected},T,A}\right) = N^2_{\text{expected},T,B}\left(\frac{1}{N_{\text{observed},T,B}} + \frac{1}{N_{\text{observed},C,B}} + \frac{1}{N_{\text{observed},C,A}}\right) \tag{2}$$

A more precise estimate can be obtained in the case of a nonideal comparison group as explained by Hauer (*14*):

$$\text{var}\left(N_{\text{expected},T,A}\right) = N^2_{\text{expected},T,B}\left(\begin{aligned}&\frac{1}{N_{\text{observed},T,B}} + \frac{1}{N_{\text{observed},C,B}} \\ &+ \frac{1}{N_{\text{observed},C,A}} + \text{var}(\omega)\end{aligned}\right) \tag{3}$$

$$\omega = \frac{r_c}{r_t} \tag{4}$$

where

$$r_c \cong \frac{N_{\text{expected},C,A}}{N_{\text{expected},C,B}} \tag{5}$$

and

$$r_t \cong \frac{N_{\text{expected},T,A}}{N_{\text{expected},T,B}} \tag{6}$$

The crash modification factor (CMF) and its variance can be estimated with Equations 7 and 8:

$$\text{CMF} = \frac{\left(\frac{N_{\text{observed},T,A}}{N_{\text{expected},T,A}}\right)}{\left(1 + \frac{\text{var}\left(N_{\text{observed},T,A}\right)}{N^2_{\text{expected},T,A}}\right)} \tag{7}$$

$$\text{var}(\text{CMF}) = \frac{\text{CMF}^2\left[\left(\frac{1}{N_{\text{observed},T,A}}\right) + \left(\frac{\left(\text{var}\left(N_{\text{expected},T,A}\right)\right)}{N^2_{\text{expected},T,A}}\right)\right]}{\left[1 + \frac{\left(\text{var}\left(N_{\text{expected},T,A}\right)\right)}{N^2_{\text{expected},T,A}}\right]^2} \tag{8}$$

where

$N_{\text{expected},T,B}$ = expected number of crashes in before period for treatment group,
$N_{\text{expected},C,A}$ = expected number of crashes in after period for comparison group,
$N_{\text{expected},C,B}$ = expected number of crashes in before period for comparison group,
$N_{\text{observed},T,B}$ = observed number of crashes in before period for treatment group,
$N_{\text{observed},T,A}$ = observed number of crashes in after period for treatment group,
$N_{\text{observed},C,B}$ = observed number of crashes in before period in comparison group,
$N_{\text{observed},C,A}$ = observed number of crashes in after period in comparison group,
ω = ratio of expected number of crashes in before and after periods for treatment and comparison groups,
r_c = ratio of expected crash count for comparison group, and
r_t = ratio of expected crash count for treatment group.

The standard error of the CMF is simply the square root of the variance as shown in Equation 8.

Before–After Study with Empirical Bayes

In the before–after study with empirical Bayes method, the expected crash frequencies at the treatment sites in the after period had the countermeasures not been implemented is estimated more precisely by using data from the crash history of a treated site, as well as the information of what is known about the safety of reference sites with similar yearly traffic trend, physical characteristics, and land use.

The method is based on three fundamental assumptions (*16*): (*a*) the number of crashes at any site follows a Poisson distribution, (*b*) the means for a population of systems can be approximated with a Gamma distribution, and (*c*) changes from year to year because of sundry factors are similar for all reference sites. A main advantage of the before–after study with empirical Bayes is that it accurately accounts for changes in crash frequencies in the before and after periods at the treatment sites that may be caused by regression-to-the-mean bias. It is also a better approach than the comparison group for accounting for influences of traffic volumes and time trends on safety. The estimate of the expected crashes at treatment sites is on the basis of a weighted average of information from treatment and reference sites as given by Persaud et al. (*15*) and Hauer et al. (*16*):

$$\hat{E}_i = (\gamma_i \times y_i \times n) + (1 - \gamma_i)\eta_i \tag{9}$$

where

y_i = number of expected crashes of given type per year estimated from the safety performance function (SPF) (represents the evidence from the reference sites),
η_i = observed number of crashes at the treatment site during the before period,
n = number of years in the before period, and
γ_i = weight factor estimated from overdispersion parameter of negative binomial regression relationship and expected before period crash frequency for treatment site:

$$\gamma_i = \frac{1}{1 + k \times y_i \times n} \tag{10}$$

where k is the overdispersion parameter that determines how widely the crash frequencies are dispersed around the mean.

The evidence from the reference sites is obtained as output from the SPF. The SPF is a regression model that provides an estimate of crash occurrences on a given roadway section. Crash frequency on a roadway section may be estimated with negative binomial regression models (*15, 18*), and therefore the negative binomial form is used to fit the SPF with before period crash data of the reference sites with their geometric and traffic parameters. A typical SPF will be of the following form:

$$y_i = e^{(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n)} \tag{11}$$

where

β_i = regression parameters,
x_1, x_2 = logarithmic values of annual average daily traffic (AADT) and section length, and
x_i = other traffic and geometric parameters of interest ($i > 2$).

The standard deviation ($\hat{\sigma}_i$) for the estimate in Equation 9 is given by

$$\hat{\sigma}_i = \sqrt{(1 - \gamma_i) \times \hat{E}_i} \tag{12}$$

The estimates obtained from Equation 9 are the estimates for the number of crashes in the before period. Because the estimated number of crashes at the treatment site in the after period must be obtained, the estimates obtained from Equation 9 are to be adjusted for traffic volume changes and different before and after periods (*15, 16*). The adjustment factors are as follows:

Adjustment for AADT (ρ_{AAD}):

$$\rho_{\text{AADT}} = \frac{\text{AADT}_{\text{after}}^{\alpha_1}}{\text{AADT}_{\text{before}}^{\alpha_1}} \tag{13}$$

Adjustment for different before–after periods (ρ_{time}):

$$\rho_{\text{time}} = \frac{y_a}{y_b} \tag{14}$$

where

$\text{AADT}_{\text{after}}$ = AADT in after period at treatment site,
$\text{AADT}_{\text{before}}$ = AADT in before period at treatment site,
α_1 = regression coefficient of AADT from SPF,
y_a = number of years in after period, and
y_b = number of years in before period.

The final estimated number of crashes at the treatment location in the after period ($\hat{\pi}_i$) following adjustment for traffic volume changes and different time periods is given by

$$\hat{\pi}_i = \hat{E}_i \times \rho_{\text{AADT}} \times \rho_{\text{time}} \tag{15}$$

The index of effectiveness ($\hat{\theta}_i$) of the treatment is given by

$$\hat{\theta}_i = \frac{\dfrac{\hat{\lambda}_i}{\hat{\pi}_i}}{1 + \left(\dfrac{\hat{\sigma}_i^2}{\hat{\pi}_i^2}\right)} \tag{16}$$

where $\hat{\lambda}_i$ is the observed number of crashes at the treatment site during the after period. The percentage reduction ($\hat{\tau}_i$) in crashes of particular type at each site (i) is given by

$$\hat{\tau}_i = \left(1 - \hat{\theta}_i\right) \times 100\% \tag{17}$$

The crash reduction factor or the safety effectiveness ($\hat{\theta}$) of the treatment averaged over all sites would be given by (*16*)

$$\hat{\theta} = \frac{\dfrac{\sum_{i=1}^{m} \hat{\lambda}_i}{\sum_{i=1}^{m} \hat{\pi}_i}}{1 + \left(\dfrac{\text{var}\left(\sum_{i=1}^{m} \hat{\pi}_i\right)}{\left(\sum_{i=1}^{m} \hat{\pi}_i\right)^2}\right)} \tag{18}$$

where m is the total number of treated sites, as based on the work of Hauer and others (*16–18*):

$$\text{var}\left(\sum_{i=1}^{k} \hat{\pi}_i\right) = \sum_{i=1}^{k} \rho_{\text{AADT}}^2 \times \rho_{\text{time}}^2 \times \text{var}\left(\hat{E}_i\right) \tag{19}$$

The standard deviation ($\hat{\sigma}$) of the overall effectiveness can be estimated with information on the variance of the estimated and observed crashes, which is given by Equation 20:

$$\hat{\sigma} = \sqrt{\frac{\hat{\theta}^2 \left[\left(\dfrac{\text{var}\left(\sum_{i=1}^{k} \hat{\pi}_i\right)}{\left(\sum_{i=1}^{k} \hat{\pi}_i\right)^2}\right) + \left(\dfrac{\text{var}\left(\sum_{i=1}^{k} \hat{\lambda}_i\right)}{\left(\sum_{i=1}^{k} \hat{\lambda}_i\right)^2}\right)\right]}{\left[1 + \left(\dfrac{\text{var}\left(\sum_{i=1}^{k} \hat{\pi}_i\right)}{\left(\sum_{i=1}^{k} \hat{\pi}_i\right)^2}\right)\right]^2}} \tag{20}$$

where

$$\operatorname{var}\left(\sum_{i=1}^{k}\hat{\lambda}_i\right)=\sum_{i=1}^{k}\lambda_i \tag{21}$$

Equation 9 was used in the analysis to estimate the expected number of crashes in the after period at the treatment sites, and then the values were compared with the observed number of crashes at the treatment sites in the after period to get the percentage of reduction in the number of crashes resulting from the treatment.

Data Description

Multiple sources of data available online and maintained by the Florida Department of Transportation were considered for identifying the traffic, geometric, and geographic characteristics of the locations, as well as for investigation and determination of the most complete and accurate data (*19*). These data sources included the Roadway Characteristics Inventory system, the TransView aerial mapping system, the Five Year Work Program, the financial project search database, and straight line diagrams. Also, Google Earth and the publication reports of Florida's Turnpike Enterprise and OOCEA (*13*) were used to verify the data. Data from 98 sites of main-line toll plazas (two directions) located on approximately 750 mi of toll roads in Florida were used. Thirty of these sites were converted from traditional to HMTP design. A total of 42 untreated sites were identified as reference sites. Reference sites are different from the comparison sites: reference sites are broader and show more variation in AADT, roadway characteristics, and crash history. An additional 26 sites were identified at which the HMTP system was implemented from the beginning; these 26 sites were not included in the analysis. However, they were used to evaluate the quality of the SPFs, CMFs, and crash modification functions.

Crash data for an 11-year period (2002 to 2012) were examined for safety impact; the crash history for 3 years before and 3 years after the implementation of the treatment was evaluated. According to the *Manual on Uniform Traffic Control Devices* (*20*), the signposting distances and the influence area of the main-line toll plaza cover 1 mi before and 0.5 mi after the centerline of the main-line toll plaza. Crashes that occurred within the influence areas of toll plazas were extracted from the Florida Department of Transportation crash analysis reporting system. Data for the period during which toll plazas were upgraded to HMTPs, including 6 months before and 6 months after, were excluded from the analysis. Figures 1 through 4 show designs and guide signs for main-line toll plazas.

FIGURE 1 Traditional main-line toll plaza (*21*).

FIGURE 2 Hybrid main-line toll plaza (*13*).

ANALYSIS AND RESULTS

Results of Naive Before–After Study

The naive before–after approach was applied to 30 main-line toll plazas that were upgraded to an HMTP. The CMFs were estimated from crash rates for individual locations and for all locations combined, and the Poisson test of significance was performed. The total crash rate across all locations was reduced from 29.59 crashes per million vehicle miles in the before period to 13.91 crashes per million vehicle miles after the implementation of HMTPs, representing about a 53% reduction in the crash rate; this reduction was statistically significant. The same approach was applied to property-damage-only (PDO) as well as fatal and injury crashes, and the results showed that HMTPs significantly reduced the levels of severity by 57.2% and 54.3%, respectively. The use of HMTP design reduced rear-end and lane-change–related crashes (i.e., sideswipe, loss-of-control, overturned, and angle crashes) by 69% and 59%, respectively.

Results for Before–After Study with Comparison Group

Data from 16 treated sites were compared with data from 16 untreated sites (these sites have similar characteristics) in the comparison group approach. Crash experience data from 16 comparison sites (traditional main-line toll plazas) were used to estimate CMFs for individual sites and for all sites combined. Crash data for 3 years before and 3 years after the treatment were used. The safety effectiveness of HMTP across all locations combined was significantly improved through reduction of total crashes (all severity) by 48%, with a standard error (SE) of 9.42%. The statistical significance of the estimated safety effectiveness was calculated as follows:

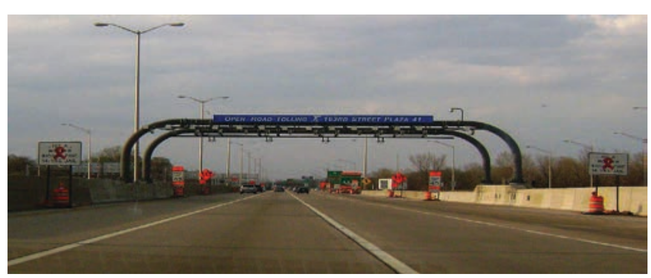
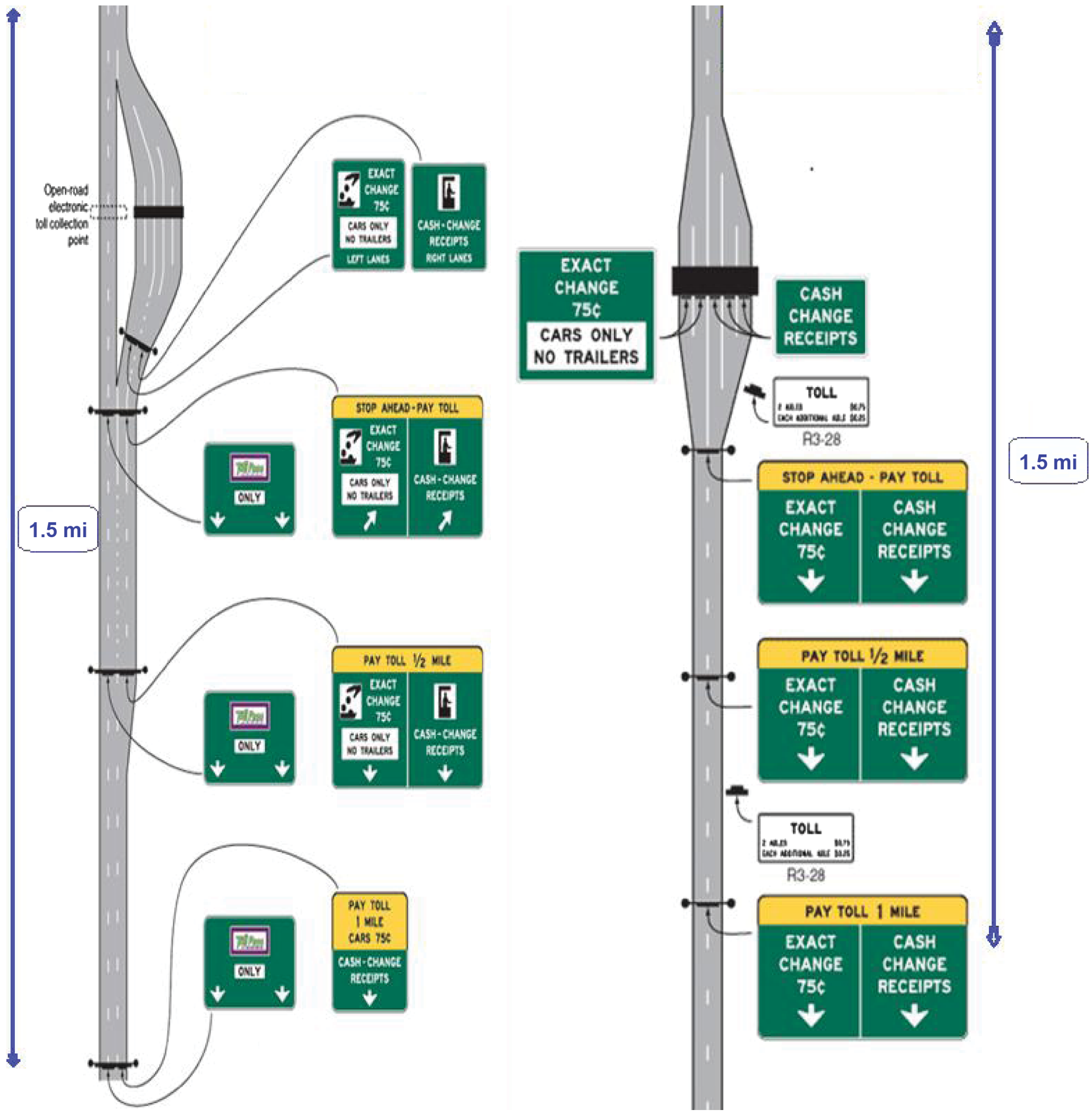


FIGURE 3 All electronic toll collection (*21*).



(a) (b)

FIGURE 4 Advance signage for (*a*) hybrid and (*b*) conventional main-line toll plaza (*20*).

$$\text{abs}\left(\frac{\text{safety effectiveness}}{\text{SE}(\text{safety effectiveness})}\right) = \frac{48}{9.42} = 5.1 \qquad (22)$$

where abs is the absolute value.

Since abs(safety effectiveness/SE (safety effectiveness)) is ≥1.96, it can be concluded that the treatment effect is significant at the 95% confidence level. The same steps were applied to PDO as well as fatal and injury crashes. The safety effectiveness across all locations combined was significantly improved by 55% and 45.2% with a standard error of 8.43% and 9.43%, respectively. Abs was statistically significant for both [abs = (4.79 and 6.52) ≥ 1.96] at the 95% confidence level as well. Similar to collision types, the treatment indicated a significant reduction for rear-end and lane-change–related crashes. The reductions were 65.3% and 57.4%, respectively. The values of abs were statistically significant at the 95% confidence level for both types of crashes. These results were consistent with previous findings that the use of an HMTP system significantly reduces the number of crashes (*2*).

Results of Before–After Study with Empirical Bayes Approach

Data from 42 reference sites at which no treatment was implemented from 2002 to 2012 were used in the empirical Bayes analysis to develop SPFs for main-line toll plazas.

Generally, SPF is a crash prediction model that relates the frequency of crashes to traffic and roadway characteristics. There are two main types of SPFs in the literature: full (FSPF) and simple (SSPF). The FSPF is a mathematical relationship that relates both traffic and geometric parameters as explanatory variables; the SSPF uses AADT as the sole explanatory variable in predicting crash frequency on a roadway entity. Negative binomial regression models for safety evaluation were developed for total crashes, severity levels, and types of crashes. SSPFs and FSPFs were developed for the main-line toll plaza. Table 1 summarizes the estimated models' parameters for the FSPFs. The results of the SSPFs were slightly different from those of the FSPFs. The Akaike information criterion (AIC) values of the

TABLE 1 Negative Binomial Regression Estimates for FSPFs

	Total[a] Crashes (coefficient)			Severity Level Coefficients, by Crash Type					
				Fatal and Injury[b]			PDO[c]		
Parameter	Estimate	Standard Error	$P > \chi^2$	Estimate	Standard Error	$P > \chi^2$	Estimate	Standard Error	$P > \chi^2$
Intercept	–9.2609	1.0614	<.0001	–9.0152	1.1002	<.0001	–10.4611	2.5545	<.0001
Log of AADT	1.3271	0.1950	<.0001	1.1128	0.1844	<.0001	1.4220	0.2738	<.0001
Speed limit	–0.0240	0.0104	.0210	0.0048	0.0105	.0474	–0.0387	0.0131	.0032
Dispersion	0.4695	0.1034	na	0.2807	0.0872	na	0.5756	0.1471	na

NOTE: na = not applicable.
[a]AIC = 308.6199.
[b]AIC = 303.229.
[c]AIC = 312.6152.
[d]AIC = 277.6112.
[e]AIC = 267.2759.

negative binomial models in FSPFs are smaller than the AIC values in the SSPFs. A smaller AIC means that the model fits better for the same data set.

The analysis showed that log AADT, the speed limit, and a downstream plaza dummy variable were the most significant variables in the final models. The signs for the parameter estimates were as expected for all crash categories.

For example, the coefficients for the traffic volume were positive, indicating that an increase in traffic volumes leads to an increase in total, fatal and injury, and all types of crashes at the main-line toll plazas. The coefficients for speed limit were negative in total crashes, indicating that an increase in the speed limit is associated with fewer crashes. However, they were positive in the fatal and injury crashes, indicating that an increase in the speed limit is associated with more severe crashes, possibly because the speed variance will increase between ETC lanes and cash lanes at the same toll plaza (approach). This speed variation most likely would contribute to more severe crashes. For the crash types, the coefficients for downstream were negative in the rear-end and lane-change–related crashes, indicating that the downstream location is associated with fewer crashes in these categories than the upstream. More research may be needed to investigate the differences between the two locations such as traffic and geometric characteristics. At HMTP sites the upstream section is associated with diverge and potential sudden lane changing, and the downstream area of the plaza would involve merging of traffic from the regular and open tolling lanes.

The empirical Bayes before–after evaluation of HMTPs was used to predict the expected crash frequency at treated sites if the HMTP had not been implemented. The expected crash frequency was compared with the number of observed crashes in the period after the HMTP had been implemented. The results showed that almost all the treated sites had a significant safety improvement.

For computing the safety impacts of the treatment, CMFs and crash modification functions were estimated with different approaches for total crashes, severity levels, and the collision types. CMFs express the safety consequences of some treatment or intervention that has been implemented on a roadway facility. A CMF greater than 1.0 indicates an expected increase in crashes; a value of less than 1.0 indicates an expected reduction in crashes after the implementation of a given countermeasure.

Table 2 presents comparisons between the CMFs resulting from the various methods [comparison group and empirical Bayes (FSPF

TABLE 2 Comparison of CMF Results for All Locations for HMTP

	Before–After with Comparison Group		Before–After			
			Univariate Empirical Bayes SSPF		Multivariate Empirical Bayes FSPF	
Crash Category	CMF [safety effectiveness (%)]	Standard Error	CMF [safety effectiveness (%)]	Standard Error	CMF [safety effectiveness (%)]	Standard Error
Total	0.52 (48)	0.09 (9.42)	0.54 (46.40)	0.08 (7.9)	**0.53** **(47.30)**	**0.05** **(5.39)**
Fatal and injury	0.55 (45.2)	0.09 (9.43)	0.51 (49)	0.09 (9.2)	**0.54** **(46.2)**	**0.07** **(6.62)**
PDO	0.45 (55)	0.08 (8.43)	0.47 (53)	0.07 (7.2)	**0.46** **(54.2)**	**0.06** **(6.22)**
Rear end	0.35 (65.3)	0.10 (10)	0.33 (67.13)	0.08 (8.4)	**0.34** **(65.6)**	**0.06** **(6.4)**
Lane change related[a]	0.43 (57.3)	0.11 (11.13)	0.46 (54.4)	0.09 (9.13)	**0.45** **(55.4)**	**0.09** **(9)**

[a]Sideswipe, loss-of-control, overturned, and angle crashes. Boldface font shows best solution.

Crash Type Coefficients, by Crash Category					
Rear End[d]			Lane Change Related[e]		
Estimate	Standard Error	$P > \chi^2$	Estimate	Standard Error	$P > \chi^2$
–9.7686	2.2221	<.0001	–11.0950	2.9216	.0001
1.1572	0.2208	<.0001	1.2329	0.2907	<.0001
–0.4605	0.2119	.0298	–0.5511	0.2726	.0432
0.2684	0.1072	na	0.3242	0.1730	na

and SSPF)] for all treated sites combined based on the standard errors. The results from the before–after with comparison group approach are almost identical to those of the multivariate empirical Bayes or FSPF. The before–after with comparison group approach and univariate empirical Bayes or SSPF provided higher standard errors than the multivariate empirical Bayes or FSPF. Therefore, for total crashes, the CMF resulting from empirical Bayes or FSPF, CMF = 0.53 (±0.05), should be used for the HMTP treatment. Similarly, for fatal and injury and PDO crashes, the comparison group method returned results closer to the multivariate empirical Bayes or FSPF with a slightly higher standard error. Thus, for the fatal and injury and PDO crashes, it is recommended that CMF = 0.54 (±0.07) and CMF = 0.46 (±0.06), respectively, be used. Similarly, for the rear-end and lane-change–related crashes, according to the lowest standard error resulting from empirical Bayes or FSPF, the best CMFs are 0.34 (±0.06) and 0.45 (±0.09), respectively.

The results in Table 3 show a linear relationship between the CMFs and the natural logarithm of AADT. This relation can be used to develop crash modification functions for all severity levels according to a location's AADT. Linear models were developed between the CMFs, AADT, and other variables. Log (AADT) was the most significant variable in the final models. The results showed an acceptable value of R^2 (.6363, .6825, and .731) for the total, PDO, and fatal and injury crashes, respectively.

The crash modification functions are as follows:

Total crashes:

$$\text{crash modification function} = 0.0541 * \ln(\text{AADT}) \tag{23}$$

Fatal and injury crashes:

$$\text{crash modification function} = 0.0401 * \ln(\text{AADT}) \tag{24}$$

TABLE 3 Estimates of Coefficients for Crash Modification Functions

Type of Crash	Log of AADT		
	Parameter Estimate	Standard Error	*P*-Value
Total	**0.05411**	0.00765	<.0001
Fatal and injury	**0.04010**	0.06240	<.0021
PDO	**0.04720**	0.008230	<.0011

PDO crashes:

$$\text{crash modification function} = 0.047 * \ln(\text{AADT}) \tag{25}$$

where ln (AADT) is the natural logarithm of AADT.

The quality of the SPFs and CMFs was evaluated through application at individual and combined location levels for 26 sites. These sites had an HMTP system from the beginning of construction and were not included in the SPF and CMF analyses. Crash data for 3 years in the after period were used. The procedure is as follows:

1. Calculate the expected number of crashes at each location by using SPFs as if the treatment had not been implemented.
2. Multiply the expected crash frequencies by the CMFs in Table 2 and the crash modification functions in Equations 23, 24, and 25 for individual and combined sites levels.
3. Compare the results with the observed crashes at these sites.

The results showed that the best CMFs for all crash categories were produced from the multivariate empirical Bayes or FSPF method. Similarly, the crash modification functions gave slightly higher errors than did the CMFs. Therefore, practitioners should use the multivariate empirical Bayes/CMF, and in future research researchers may build on the crash modification functions.

CONCLUSIONS

This study evaluated the safety effectiveness of upgrading traditional main-line toll plazas to HMTPs. Data from 98 sites located on approximately 750 mi of toll roads in Florida were used; 30 of the sites were upgraded to HMTPs. Crash data from an 11-year period (2002 to 2012) were used; 3 years of crash data before and 3 years after the implementation of HMTPs were evaluated.

The safety effectiveness of HMTPs was estimated with several observational before–after studies: naive before–after, before–after with comparison group, and before–after with empirical Bayes approaches. Negative binomial regression models were used to develop the main-line toll plazas' specific SPFs. The analysis focused on total crashes, PDO crashes, fatal and injury crashes, and crash types.

The analysis showed that the best crash modification factors for all crash categories were produced by the multivariate FSPF/empirical

Bayes method, and its results indicated that the conversion from traditional main-line toll plaza design to an HMTP system resulted in an average crash reduction of 47%, 46%, and 54% for total crashes, fatal and injury crashes, and PDO crashes, respectively. The use of HMTP design significantly reduced rear-end crashes and lane-change–related crashes (i.e., sideswipe, loss of control, overturned, and angle crashes) by an average of 65% and 55%, respectively.

The use of HMTP design was proved to be an excellent solution for several traffic operations, as well as for environmental and economic problems. The results of this study proved that the safety effectiveness was significantly improved across all locations that were upgraded to HMTP.

Locating toll plazas at safe distances from the interchanges and finding ways to increase the percentage of ETC users are potential means of reducing lane changes at these facilities.

For practitioners, use of the multivariate empirical Bayes–CMF results is recommended. Future research may build on the crash modification functions developed in this study.

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All opinions and results are solely those of the authors.

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