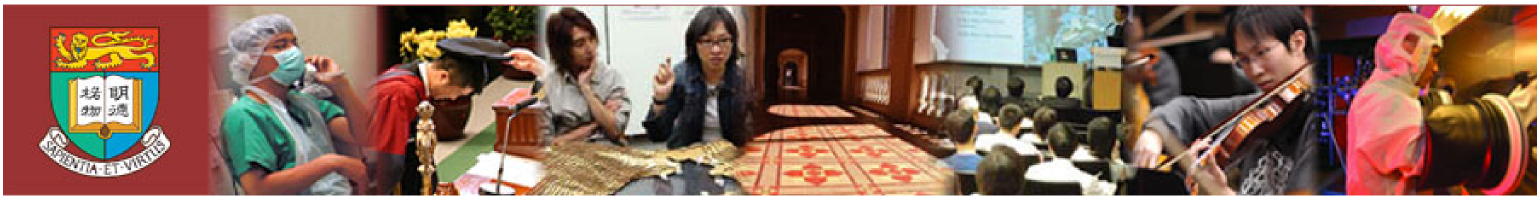

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Traffic crashes at toll plazas in Hong Kong

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Poisson regression was used to identify the significant contributory factors to traffic crashes at toll plaza areas in Hong Kong. Information on the crash incidences and traffic volume at the toll plaza areas of ten tolled roads in Hong Kong during 1998–2003 were obtained from the traffic accident database system and annual traffic census of the Transport Department of the Government of Hong Kong Special Administrative Region. These data, together with the geometric and operational characteristics, including toll plaza width, carriageway width, degree of road curvature, road gradient, and toll booth configuration, were incorporated into two aggregated crash predictive models for different traffic directions. The results revealed that the crash likelihood of inbound traffic was increased significantly with downward slope and the crash likelihood of outbound traffic increased with the degree of road curvature.

1. INTRODUCTION

In Hong Kong, new towns have been developed to cope with the population growth since the late 1970s, and more and more people have opted to live further away from the core areas.[1] To cope with the dispersed demand pattern, it has long been a common practice for vehicles to travel to and from different parts of Hong Kong by tolled tunnels or expressways to reduce travel time and cost. Booths to collect the toll fees are set up near tunnel portals and on different sections of expressways. To accommodate queuing traffic, these booths are collectively assigned a specially designed area—a toll plaza—which has different crash characteristics from those of other parts of the tunnel or expressway because of its geometric design and the speed and weaving movements of vehicles in the area.

Many studies have been carried out to examine the performance of toll plazas for different configurations and toll collection methods. A traffic simulation model was established to evaluate the operational performance of toll plazas with a car following and lane changing algorithm.[2] Delay and service time were assessed to define the level of service and efficiency of toll plazas.[3] Furthermore, the level of service based on traffic density, volume-to-capacity ratio, and average delay were quantified to evaluate the operational performance of toll plazas, with information obtained from a field survey and a simulation model.[4]

The introduction of an electronic toll collection (ETC) system, which in Hong Kong is known as 'auto-toll', noticeably improved the operational performance of toll plazas, especially during the peak hours. A qualitative comparison of manual and ETC systems can be found in Hau.[5,6] Particular studies that addressed the effect of an innovative toll collection system on the planning, design, operation, and management of tolled roads were carried out. The increase in the ETC subscription rate greatly improved efficiency because of an appreciable reduction in total delay and queue length.[2] A before-and-after survey was conducted to evaluate the operational performance of toll plazas that had additional express toll gates installed.[7] After the redesign of the plaza configuration, and thus the enhancement in toll collection management and tunnel operation, the overall capacity sharply increased by 44% because of the substantial reductions in service and inter-vehicle time.

Traffic engineers were, however, also interested in the safety performance of toll plazas. Logit model and artificial neural networks were applied to estimate the crash risk and injury severity at different locations of toll plazas.[8] The heavy-duty trucks, older drivers, and vehicles in the upstream of toll plazas were found to have a relatively higher injury risk. In addition, the effect of ETC on toll plaza safety due to high-speed traffic through the corresponding toll lanes has attracted the attention of many researchers.[9] In addition, an observational study was conducted to evaluate the operational and safety performance after the implementation of new guidance signs and road markings for ETC users.[10] The crash risk was reduced because clearer road signs had been erected, which assisted drivers who were searching for an appropriate path when approaching the ETC gates.

Indeed, the development of comprehensive guidelines that regulate the design, planning, construction, and operation of toll plazas is essential for more efficient management and better safety performance. Comprehensive toll plaza design guidelines within the categories of a horizontal and vertical geometric configuration were established,[11] for which the optimum design parameters on flare length, queue area length, toll lane width, toll-booth configuration, and gradient for better operation and safety performance were recommended.

Efforts have long been made to establish a crash predictive model for urban highways and intersections. Negative binomial regression and Poisson regression models were used to estimate the crash risk at highway–rail interfaces.[12] To improve the prediction performance, the random effect negative binomial model was constructed to predict crash occurrence at signal-controlled intersections.[13] A similar approach was also adopted to determine the crash risk for urban road networks.[14] Road design and geometric characteristics were confirmed to be significant contributory factors to crashes on urban road links. In Hong Kong, Poisson regression and negative binomial regression models have been applied to determine the likelihood of a slight injury crash and that of fatal and serious injury crashes at signal-controlled intersections.[15] Similar studies on toll plazas, especially in evaluating the associations between crash risk and design geometries, were, however, rare.

The present study aimed to develop crash predictive models that employ information on traffic volume, geometric parameters, operational characteristics and crash incidence for toll plazas in Hong Kong. Poisson regression was applied to determine the associations between crash occurrence, the geometric characteristics of road gradient, degree of road curvature, toll plaza width, carriageway width and lane configuration, while controlling for the influence of exposure that is represented by the traffic volume.

2. DATA

In the present study, the crash and traffic information at the toll plaza areas in Hong Kong for the nine tolled tunnels and the Lantau Link during the period 1998–2003 was analysed. Crash information was obtained from the traffic accident database system (Trads) that is maintained by the Transport Department. As an indication of the overall safety performance in Hong Kong, the fatality rates were 0·024 per 1000 population, 0·495 per 1000 vehicles, 0·085 per kilometre of road length, and 0·014 per million vehicle–km in the year 2000.[16] The traffic flow data were taken from the annual traffic census.[17–19] Information on the geometric parameters, including toll plaza width, carriageway width, flare length, road gradient, and degree of road curvature on approach roads, was obtained from the layout plan and field study for each plaza that was studied. The degree of road curvature was evaluated as the reciprocal of the turning radius for the centre-line of the road segment concerned. A straight segment was denoted by zero, and the reciprocal increased with the degree of road curvature.

The implementation of an electronic toll collection system (auto-toll) noticeably enhances the operational efficiency and increased the capacity of toll plazas. Vehicular speed in the auto-toll lane is relatively higher than that in ordinary lanes, however, and the lane-cutting movements that occur between ordinary and auto-toll lanes are considered to be risky. Thus, a weaving ratio, which was a specific variable that denoted the ratio of the number of lane-cutting movements across auto-toll lanes to the number of all possible lane-cutting movements, was calculated in an attempt to quantify the influence of lane configuration on safety.

Traffic volume is an efficient indicator of the influence of exposure and traffic intensity on the crash incidence. More importantly, the intervention of exposure on the association between primary contributory factors and crash risk, which is the crash count divided by the traffic volume, should be properly accounted for. In this study, the logarithmically transformed average annual daily traffic (AADT) was applied to reveal the proportionality of the relationship between the crash risk and traffic volume.

Separate models were established for inbound (approaching the tunnel or expressway portal) and outbound (leaving the tunnel or expressway portal) traffic. The Lantau Link toll plaza uses a one-way toll collection arrangement. When travelling through the Lantau Link, drivers only have to pay the double toll when they leave (inbound), but do not have to pay anything when they enter (outbound). Hence, no toll gate has been erected and only three lanes are open to traffic on the airport-bound carriageway (outbound) at the Lantau Link toll plaza, and so this was excluded from the proposed model. Hence, there were 54 observations for outbound traffic. The diagnosis of information on crash data, traffic volume, toll plaza geometry and operation attributes is illustrated in Table 1.

	Inbound traffic (number of observations = 60)				Outbound traffic (number of observations = 54)			
	Min.	Max.	Mean	Standard deviation	Min.	Max.	Mean	Standard deviation
Dependent variable:								
Crash incidence	0	9	2·83	2·13	0	10	3·13	2·56
Exposure:								
log (AADT)	9·48	11·03	10·29	0·38	9·58	10·99	10·37	0·35
Independent variables:								
Road gradient	−0·04	0·03	0·01	0·02	−0·04	0·04	0·00	0·03
Weaving ratio	0·14	0·40	0·25	0·08	0·14	0·40	0·27	0·10
Road curvature	0	0·00208	0·00081	0·00086	0	0·00667	0·00092	0·00210
Toll plaza width	30·00	50·00	36·00	7·09	29·00	47·00	35·00	5·01
Carriageway width	9·00	24·00	14·35	4·16	6·50	14·00	9·11	2·36
Flare length	121·00	345·00	192·80	68·60	148·00	320·00	214·67	48·84

Table 1. Summary of variables in the crash predictive models

	log (AADT)	Road gradient	Weaving ratio	Road curvature	Toll plaza width	Carriageway width	Flare length
log (AADT)	1·00	−0·12	0·01	0·16	−0·68	−0·29	−0·69
Road gradient	−0·12	1·00	0·12	0·34	−0·02	−0·23	−0·08
Weaving ratio	0·01	0·12	1·00	0·33	−0·63	−0·25	−0·45
Road curvature	0·16	0·34	0·33	1·00	−0·54	−0·23	−0·60
Toll plaza width	−0·68	−0·02	−0·63	−0·54	1·00	0·51	0·95
Carriageway width	−0·29	−0·23	−0·25	−0·23	0·51	1·00	0·42
Flare length	−0·69	−0·08	−0·45	−0·60	0·95	0·42	1·00

Table 2. Results of correlation analysis for inbound traffic

3. POISSON REGRESSION

The objective of this study was to determine the significance of operational and geometric characteristics that contribute to crash occurrences at toll plaza areas. The crash predictive model, which involves the discrete, non-negative, and sporadic crash count as a dependent variable, could not be adequately modelled by linear regression. The Poisson regression, which efficiently approximates the rare-event count variable,[20] was therefore employed.

The basic assumption for a Poisson distribution is that the mean and the variance are equal. An overdispersion test[21] was conducted to verify the suitability of Poisson estimation for the proposed crash predictive models.

In addition, the independent variables that are incorporated into the multivariate model should not be significantly correlated. The violation of this assumption is known as multicollinearity. When multicollinearity exists between independent variables, the standard error of the coefficient estimate is significant, in which case the proposed model may be biased. We took great care in the selection of independent variables to be incorporated into the crash predictive models. Correlation analysis was conducted to resolve the problem associated with multicollinearity so that problematic combinations of the offending variables would be prevented in the subsequent association measures. Based on the results of correlation analysis (as shown in Tables 2 and 3), toll plaza width and flare length were eliminated from the crash predictive model for inbound traffic, and weaving ratio, carriageway width and flare length were eliminated from the crash predictive model for outbound traffic.

Poisson regression was applied to determine the influence of geometric design and various attributes on the crash incidence at toll plaza areas, controlling for the influence of traffic volume that was represented by the logarithmically transformed AADT. As shown in Table 4, for inbound traffic, road gradient (coefficient = −8·92, t-statistic = −2·28) significantly determined the crash likelihood at the 5% level. The downward sloping road segment seemingly led to a greater crash likelihood for inbound traffic at toll plazas. The traffic volume (coefficient = 0·40, t-statistic = 1·79) and degree of road curvature (coefficient = 202·05, t-statistic = 1·85) marginally determine the crash incidence of inbound traffic at toll plazas at the 10% significance level. The crash incidence increase was proportionately less than the increase in traffic volume. In other words, the crash risk decreased as the traffic volume increased.

For outbound traffic, the degree of road curvature (coefficient = 147·81, t-statistic = 3·32) significantly determined the crash likelihood at the 1% level, which meant that crashes were more likely to occur on the curved road segment. Traffic volume did not significantly determine the crash likelihood of outbound traffic.

The proposed crash predictive models fitted adequately well with the observed crash counts at the 1% significance level, for both inbound (chi-squared statistic = 16·14) and outbound (chi-squared statistic = 45·38) traffic. In addition, no significant overdispersion could be found (inbound: t-statistic = 1·24; outbound: t-statistic = 0·51) at the 95% confidence level, which justified the application of the Poisson regression model.

However, the use of temporal crash data from each toll plaza might induce some concern about the model specification, when considering the violation of the independence assumption over

	log (AADT)	Road gradient	Weaving ratio	Road curvature	Toll plaza width	Carriageway width	Flare length
log (AADT)	1·00	−0·32	0·17	0·40	−0·59	−0·18	−0·75
Road gradient	−0·32	1·00	−0·72	−0·59	0·61	0·88	0·24
Weaving ratio	0·17	−0·72	1·00	0·44	−0·55	−0·67	−0·07
Road curvature	0·40	−0·59	0·44	1·00	−0·30	−0·22	−0·15
Toll plaza width	−0·59	0·61	−0·55	−0·30	1·00	0·74	0·81
Carriageway width	−0·18	0·88	−0·67	−0·22	0·74	1·00	0·34
Flare length	−0·75	0·24	−0·07	−0·15	0·81	0·34	1·00

Table 3. Results of correlation analysis for outbound traffic

	Inbound		Outbound	
	Coefficient	(*t*-statistic)	Coefficient	(*t*-statistic)
Variables:				
Constant	−2·44	(−0·97)	−0·94	(−0·24)
log (AADT)	0·40	(1·79)*	0·25	(0·78)
Road gradient	−8·92	(−2·28)**	−1·08	(−0·21)
Weaving ratio	−1·28	(−1·04)	–	
Road curvature	202·05	(1·85)*	147·81	(3·32)***
Toll plaza width	–		−0·02	(−0·81)
Carriageway width	−0·03	(−1·45)	–	
Goodness-of-fit test:				
Log-likelihood at convergence	−117·86		−104·26	
Log-likelihood at zero	−125·93		−126·94	
Number of observations	60		54	
Degree of freedom	5		4	
Chi-squared statistic, χ^2	16·14***		45·38***	
Overdispersion test:				
$g[E(y_i)] = E(y_i)$	1·24		0·51	
$g[E(y_i)] = [E(y_i)]^2$	1·11		−0·23	
Internal consistency test:				
Log-likelihood at convergence for				
1998	−16·00		−14·52	
1999	−28·04		−16·51	
2000	−17·49		−13·61	
2001	−14·84		−14·27	
2002	−17·83		−19·27	
2003	−14·89		−18·07	
Chi-square statistic, χ^2	17·53†		16·02†	

* Statistically significant at the 10% level.
** Statistically significant at the 5% level.
*** Statistically significant at the 1% level.
† Passed the internal consistency test at the 95% confidence level.

Table 4. Results of Poisson regression

observations.[22] A likelihood ratio test that was based on the segmentation of data was applied to ensure the temporal consistency of model estimation results.[23] To evaluate the effect of possible correlation on model estimation, the data were split into six subsets by year, and the log-likelihood at convergence for all subsets was determined in comparison with that of the overall data sample. The test statistics of 17·53 and 16·02 (Table 4) for inbound and outbound traffic, confirm the temporal consistency of the proposed models at the 95% confidence level.

4. DISCUSSION

In the present study, factors that significantly contribute to the occurrence of crashes at toll plazas were identified by a Poisson regression model, for which the intervention effects by traffic volume on the association measures were considered.

For inbound traffic, the crash likelihood generally increased with the traffic volume, probably because of the increasing merging activities that involve a greater degree of interaction between vehicles. However, the coefficient that was associated with log (AADT) was 0·4, which is less than unity. It means that the crash risk seemingly decreased with the increase in traffic volume, which may be attributable to the fact that traffic slows down at busy toll plazas, thus reducing the risk of losing control and other speed-related factors which are related to traffic crashes. This non-linear relationship between traffic volume and crash likelihood was consistent with previous findings, in which the coefficient that was associated with log (AADT) ranged from 0·25 to 0·75.[15,24,25]

For outbound traffic, the crash likelihood was not sensitive to the increases in traffic volume, probably because the traffic diverges when leaving the tunnel or expressway portal which involves a lower degree of interaction between vehicles. However, the impacts of primary contributory factors on the crash risk at toll plaza areas could be efficiently quantified when the influence of exposure was explicitly controlled with the logarithmically transformed AADT.[15]

For inbound traffic, a significant association was found between crash occurrence and road gradient, for which downward sloping approach roads had a higher crash risk. The likelihood of crashes increased on downward sloping roads because the time that was required to carry out a defensive manoeuvre in response to a sudden lane change or braking on the part of another vehicle increased under the influence of gravity.[26] It is recommended that more advanced signage and road markings be positioned further from the toll plaza to warn drivers. Proper guidance road markings and signage, which would assist with the lane-searching process for both auto-toll and non-auto-toll users, would improve the safety performance of toll plazas.[10]

On the other hand, road curvature increased the crash likelihood. This was because the visibility decreased with road curvature, thereby preventing drivers from identifying the appropriate path for the correct toll gate and causing them to engage in last-minute lane changing that induced vehicle conflicts. Outbound traffic was more sensitive to the adverse impact of the degree of road curvature on crash risk because of the substantial change in light intensity for traffic that is coming out of the tunnels. Therefore, proper warning signs, road markings, and a more adhesive road surface could help when a reduction in road curvature is impractical in certain circumstances due to topological constraints.

5. CONCLUSIONS

The present study was the first attempt to quantify the relationship between crash incidence, traffic, and the geometric design of toll plazas in Hong Kong using Poisson regression. The intervention of traffic volume on the association between crash risk and primary contributory factors were efficiently controlled for by using the logarithmically transformed AADT. For inbound traffic, downward sloping roads led to a significantly higher crash risk, whereas the increase in road curvature marginally increased the crash risk. For outbound traffic, crash likelihood increased with the degree of road curvature.

The explanatory factors that were illustrated in the current study should not be regarded as the only factors that contribute to crash occurrence at toll plazas. Weather, vehicular speed, traffic composition, the road environment, and driver attributes are known to be possible immediate contributory factors to crash and injury risk at the disaggregate level. These factors, however, were not considered in the current study which focused on the aggregate model based on the annual crash incidence data.

Moreover, the explanatory power of the proposed model could be limited to its sample size and the level of observed count. Lengthening the observation period and increasing the sample size could effectively address the problem that was associated with the spatial and temporal disturbances of crash risk.

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