PENERBITAN PEGAWAI

Development of prediction models for motorcycle crashes at signalized intersections on urban roads in Malaysia

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ABSTRACT

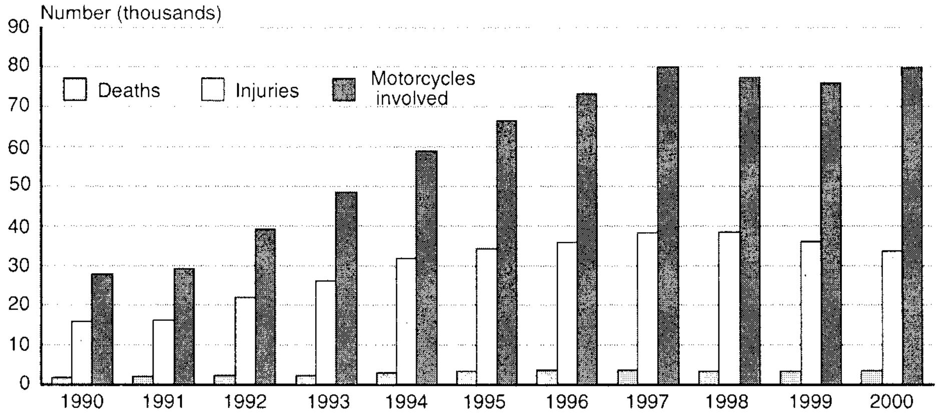
Because more than half the motor vehicles in Malaysia are motorcycles, safety of this form of transportation is an important issue. As part of a motorcycle safety program, Malaysia became the first country to provide exclusive motorcycle lanes in the hopes of reducing motorcycle crashes along trunk roads. However, little work has been done to address intersection crashes involving motorcycles. This paper provides models for predicting motorcycle crashes at signalized intersections on urban roads in Malaysia. A generalized linear modeling technique with quasi-likelihood approach was adopted to develop the models. Traffic entering the intersection, approach speed, lane width, number of lanes, shoulder width, and land use at the approach of the intersection were found to be significant in describing motorcycle crashes. These findings should enable engineers to draw up appropriate intersection treatment criteria specifically designed for motorcycle lane facilities in Malaysia and elsewhere.

INTRODUCTION

Motorcycle crashes continue to be a problem in both developing and developed countries. Fatality rates (measured in deaths per 10,000 registered

KEYWORDS: Motorcycle crashes, generalized linear models, prediction model, intersection crashes, motorcycle crash model.

FIGURE 1 Motorcycle Crashes in Malaysia: 2000



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Deaths	1,826	2.062	2,307	2,416	2,946	3,362	3,778	3,760	3,409	3,410	3,519
Injuries	15,857	16,235	21,957	26,226	31,957	34,372	35,960	38,317	38,448	36,100	33,651
Motorcycles involved	27,845	29,225	39,272	48,511	58,921	66,508	73,268	80,100	77,298	76,032	79,816

Source: Polis Di Raja Malaysia, *Statistical Report: Road Accidents, Malaysia 2000* (Kuala Lumpur, Malaysia: 2002, Traffic Branch, Royal Malaysian Police).

vehicles) in these crashes are much higher than in nonmotorcycle[1] crashes. In the United States, the National Highway Traffic Safety Administration (USDOT 2002) reported a fatality rate of 6.5 per vehicle-miles traveled, and motorcyclists were about 26.1 times as likely as passenger car occupants to die in a motor vehicle traffic crash. The Canadian rate was 4.7 in 1999, which rose to 5.1 in 2000; the Canadian nonmotorcycle fatality rate in 2000 was 0.7 (Transport Canada 2001). Similarly large rates have been reported in other developed countries: Australia's rate was 6.2 in 2001, an increase of about 9% from 2000 and more than 4 times the fatality rate of other road users (ATSB 2002); the United Kingdom's rate was 7.3 in 2000, decreasing to 6.6 in 2001, about 10 times the fatality rate for passenger car occupants (DfT 2002); Swedish (SI 2000), French, and German (OECD 2002) rates in 2000 were 4.1, 5.3, and 2.2, respectively.

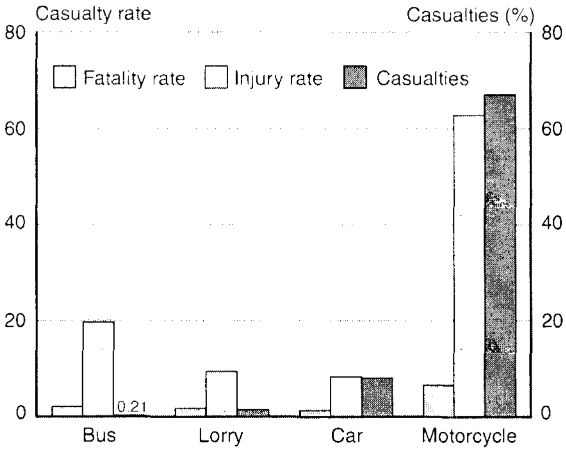
In developing countries, deaths and serious injuries from motorcycle accidents constitute a large portion of total road casualties especially in Asian countries, because motorized two-wheelers make up 40% to 95% of their vehicle fleets. As a result, more than half the road fatalities were riders or pillion passengers.

In Malaysia, motorcycles constitute more than half the total vehicle population and contribute more than 60% of the casualties (deaths and serious and slight injuries) in traffic crashes. In 2000, 79,816 crashes involved motorcycles, an increase of almost three-fold from 1990. Of these, almost 3,000 motorcyclists were killed every year during this period (figure 1). Moreover, motorcyclist casualties were much higher than those of occupants in other types of vehicles (figure 2).

In an attempt to reduce casualties, exclusive motorcycle lanes were constructed along major trunk roads in the country. Since the implementation of this initiative, a number of studies (Radin 1996; Radin et al. 1995, 2000) have been carried out to evaluate the impact of these lanes on motorcycle crashes on highway links. Results indicate the lanes had a significant effect ($p < 0.01$), reducing motorcycle crashes by 39% following the opening of the lanes to traffic. However, little research has been done on motorcycle crashes at intersections. Indepth studies would allow traffic engineers to establish appropriate intersection treatment criteria specifically designed for motorcycle lane facilities.

[1] Nonmotorcycle refers to all types of motorized vehicles excluding motorcycles.

FIGURE 2 Motorcycle Rider Casualties Compared with Casualties for Occupants in Other Types of Vehicles: 2000



Key: Fatality rate = fatalities per 10,000 registered vehicles; injury rate = injuries per 10,000 registered vehicles; casualties (%): as a percentage of all casualties in traffic crashes in Malaysia.

Source: Polis Di Raja Malaysia, *Statistical Report: Road Accidents, Malaysia 2000* (Kuala Lumpur, Malaysia: 2002, Traffic Branch, Royal Malaysian Police).

Recent studies on traffic crash modeling have used the generalized linear modeling (GLM) approach (McCullagh and Nelder 1989) with Poisson or negative binomial error structure. This approach is widely accepted as more appropriate for the characteristics of crashes (i.e., discrete, rare, and independent) than the classical linear model based on normal error structure with a constant variance. Crashes can be characterized by their mean number per unit time and are simply represented by a Poisson random variable.

Many researchers have reported the usefulness of the GLM approach in developing predictive models for traffic crashes using either cross-sectional or time series analysis (Griebe and Nielsen 1996; Mountain et al. 1996, 1998; Tarko et al. 1999; Vogt and Bared 1998; Vogt 1999; Radin et al. 1995, 2000; Radin 1996; Bauer and Harwood 2000; Saied and Said 2001; Taylor et al. 2002). For example, an earlier study on crashes at intersections prepared for the Federal Highway Administration of the U.S. Department of Transportation in connection with the development of the Interactive Highway Safety Design Model (IHSDM) (Bauer and Harwood 2000) provided direct input into the Accident Analysis Module of the IHSDM.

The analysis included all collision types using three-year crash frequencies (1990 to 1992) and geometric design, traffic control, and traffic volume data from a database provided by the California Department of Transportation. The analysis was performed using the SAS GENMOD procedure. The models were developed using the GLM approach with a log-normal regression model and a loglinear regression model (a Poisson regression followed by a negative binomial regression model). In this study, the 10% significance level of the *t*-statistic of the parameter estimates was used to assess the significance of the fitted model. The explanatory variables (continuous and categorical) that follow were found to be significant in explaining crashes at intersections:

- major road ADT (average daily traffic) and minor road ADT,
- average lane width on major roads,
- number of lanes on major and minor roads,
- design speed of major roads,
- major-road right-turn and left-turn channelizations,
- access control on major roads,
- functional class of major roads,
- outside shoulder width on major roads,
- terrain,
- road lighting,
- minor-road right-turn channelization,
- major-road left-turn prohibition, and
- median on major roads.

As an extension to our earlier analysis (Harnen et al. 2003a, 2003b), this paper presents the development of prediction models for motorcycle crashes at signalized intersections along both the exclusive and non-exclusive motorcycle lanes on urban roads in Malaysia. We used the GLM approach with Poisson error structure to develop our models. The parameter estimates and tests of their significance were carried out using GLIM 4 statistical software (NAG 1994), which is specifically designed for fitting generalized linear models.

THE DATA

Selected Intersections

The intersections studied were located on urban roads in four districts of the state of Selangor, Malaysia. The data collected covered motorcycle crashes, traffic and pedestrian flow, approach speed, intersection geometry, number of legs, and land use. The intersections were selected based on the following conditions between 1997 and 2000: a) only marginal change in land use; b) no major modifications or upgrading; c) an equal number of lanes on the corresponding major and minor roads; d) only marginal change of signal characteristics, for example, signal timing and signal phasing; e) no access road within a 50 meter distance from the intersection stop lines; and f) intersections must have had fatalities and/or serious and slight injuries in crashes. It should be noted here that while data were collected on signal characteristics they were not analyzed for this paper; however, they will be included in future work. Based on the intersection files (142 signalized intersections with motorcycle crashes in the period 1997 to 2000) extracted from the Microcomputer Accident Analysis Package (MAAP) database and visits to the sites to ensure that they met the requirements, 51 intersections were chosen. In this study, motorcycle crashes occurring within 50 meters of the corresponding stop lines of the intersection were classified as intersection crashes.

Motorcycle Crash Data

Four-year's worth of motorcycle crash data on the selected intersections, from 1997 through 2000, were collected from the police crash record form, POL 27 (Pin 1/91). The POL 27 is designed for easy completion (Radin et al. 1993) and is fully compatible with the MAAP database developed by the Transport Research Laboratory (Hills and Baguley 1993). Data were extracted from two complementary sources: the MAAP database for fatal and serious injury crashes, and the Computerized Accident Recording System (CARS 2000) database for slight injury crashes. Both databases are based on the POL 27 record form.[2]

[2] The MAAP database is located at the Road Safety Research Center, Universiti Putra Malaysia, while the CARS 2000 database is located at the Traffic Branch, Royal Malaysian Police Headquarters.

Traffic Flow Data

In this study, the estimated annual average daily traffic (AADT) defines the traffic flow on each selected intersection. Hourly traffic volume (disaggregated by nonmotorcycles and motorcycles) was counted on major- and minor-road approaches and then converted to AADT by using hourly, daily, and monthly factors. These factors were determined based on 24-hour permanent traffic count station and traffic census data, available from the Highway Planning Unit, Ministry of Works in Malaysia (HPU 2001a, 2001b) and were developed using the method proposed by McShane et al. (1998). The AADT is expressed in terms of the number of nonmotorcycles per day and motorcycles per day.

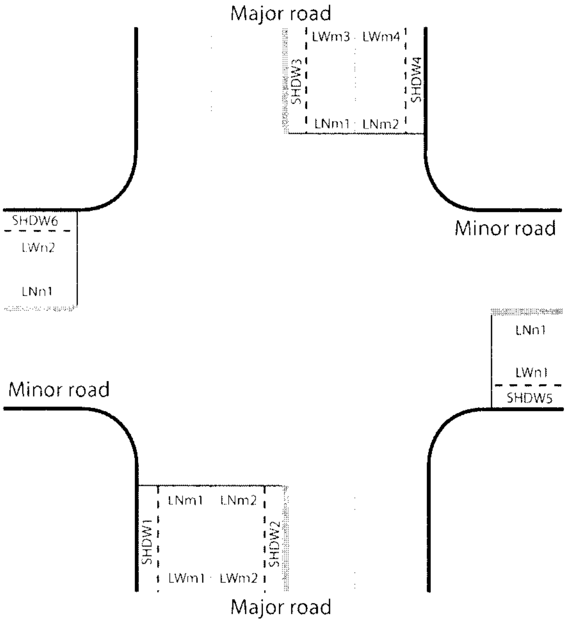
Other Data Used

Approach speed and pedestrian flow were also considered in this study. However, while these data were not available in the database, they were collected onsite following criteria used by Golias (1997) in an earlier study. The 85th percentile approach speed on major and minor roads was used to represent the approach speed on each intersection. Arndt and Troutbeck (1998) also considered this characteristic in an earlier study on traffic crashes. The approach speeds were measured at a 50 meter distance upstream from the corresponding stop lines of the intersection and were counted for all vehicles moving during the time the signal was green.

Pedestrian flow at each intersection was defined as the total number of pedestrian crossings per hour counted on major- and minor-road approaches. It should be noted that pedestrians per hour rather than pedestrians per day was used to express pedestrian flows at intersections. This was done because there was no supporting data to convert hourly pedestrian flow to annual average daily pedestrians (the AADT for pedestrians).

Intersection geometry, number of legs, and land use for each selected intersection were also observed onsite. Of the 51 selected intersections, 27 were three-legged while 24 were four-legged. The land use adjacent to the intersection was classified into two categories: commercial and noncommercial areas. A commercial area was defined as an area with a concentration of offices, shops, and railway and bus stations, while residential areas and unused land come under the category of noncommercial

FIGURE 3 Typical Layout of Intersection Geometry



Key: LWm1, 2, 3, 4 = lane width on major road approaches;
LWn1, 2 = lane width on minor road approaches;
LNm1, 2 = number of lanes on major road approach;
LNn1 = number of lanes on minor road approach;
SHDW1, 2, 3, 4, 5, 6 = shoulder width on major- and minor-road approaches.

area. Of the 51 intersections, 33 were located in commercial areas and 18 were in noncommercial areas. Figure 3 shows a typical layout of intersection geometry considered in the study.

MODEL DEVELOPMENT

Prior to carrying out the statistical modeling, we did some preliminary work to facilitate the modeling process. This included formulating the theoretical models, specifying the error structure and link function, identifying the model variables, and defining the goodness-of-fit and significance tests.

Using our earlier analysis of motorcycle crashes at intersections (Harnen et al. 2003a, 2003b) and studies of traffic crashes at intersections (Griebe and Nielsen 1996; Vogt and Bared 1998; Vogt 1999; Bauer and Harwood 2000; Saied and Said 2001), we defined the model structure and the variables included.

Two separate models (Models 1 and 2) were proposed. These models used the same data and structure but employed different explanatory variables. In Model 1, the response variable was the number of motorcycle crashes and the explanatory variables were traffic flow (disaggregated by nonmotorcycles and motorcycles both for major and minor roads), pedestrian flow, approach speed, lane width, number of lanes, number of legs, shoulder width, and land use. The continuous variables were identified as traffic flow, pedestrian flow, approach speed, lane width, and number of lanes, while the categorical variables were number of legs with two-factor levels, shoulder width with three-factor levels, and land-use with two-factor levels. In Model 2, the response variable was motorcycle crashes, while the explanatory variables were traffic flow and shoulder width. Both traffic flow and shoulder width were continuous variables.

The main differences in these two models are the explanatory variables included. Model 2, which has three continuous variables, is simpler than Model 1 and can be used further to establish major- and minor-road flow criteria for intersection treatment. This can be done by using the design curves relating major- and minor-road flows and shoulder widths developed based on Model 2.

Model 1, which has 13 variables (combination of continuous and categorical), was aimed at giving more room to engineers for analyzing the variables contributing to motorcycle crashes. Software that is specifically designed for Model 1 application could make it easier and faster to analyze the variables and estimate motorcycle crashes.

Taking the earlier studies on intersection crash modeling into consideration, the theoretical models containing all terms used in this study were formulated as follows:

Model 1

$$MCA = k_1 QNMm^{\alpha_1} \bullet QNMn^{\alpha_2} \bullet QMm^{\alpha_3} \bullet QMn^{\alpha_4} \bullet QPED^{\alpha_5} \bullet \mathrm{EXP}^{z} \quad (1)$$

where

$$z = \beta_1 SPEED + \beta_2 LWm + \beta_3 LWn + \beta_4 LNm + \beta_5 LNn + \beta_6 NL + \beta_7 SHDW + \beta_8 LU + e$$

Model 2

$$MCA = k_2 Qmajor^{\delta_1} Qminor^{\delta_2} \mathrm{EXP}^{(\lambda_1 SHD + e)} \quad (2)$$

where MCA is motorcycle crashes per year. Descriptions of all the explanatory variables are presented in table 1. The k_1, k_2, α_1, α_2, α_3, α_4, α_5, β_1, β_2, β_3, β_4, β_5, β_6, β_7, β_8, δ_1, δ_2, and λ_1 are the parameters to be estimated and the (*e*) term is the error representing the residual difference between the actual and predicted models.

Using a logarithmic transformation, the loglinear version of the model is:

Model 1

$$
\begin{aligned}
Ln(MCA) = {} & Ln(k) + \alpha_1 Ln(QNMm) + \alpha_2 Ln(QNMm) \\
& + \alpha_3 Ln(QMm) + \alpha_4 Ln(QMn) + \alpha_5 Ln(QPED) \\
& + \beta_1(SPEED) + \beta_2(LWm) + \beta_3(LWn) + \beta_4(LNm) \\
& + \beta_5(LNn) + \beta_6(NL) + \beta_7(SHDW) + \beta_8(LU) + e \qquad (3)
\end{aligned}
$$

Model 2

$$
\begin{aligned}
Ln(MCA) = {} & Ln(k) + \delta_1 Ln(Qmajor) \\
& + \delta_2 Ln(Qminor) + \lambda_1(SHD) + e \qquad (4)
\end{aligned}
$$

To allow direct interpretation of the parameter estimates produced by GLIM 4, the flow functions in equations (3) and (4) need to be transformed using a natural logarithmic (*Ln*), while the others do not. It should be noted that the total four-year crash frequencies were used to fit the models. However, by introducing an offset variable in the fitting process, the final model would be able to estimate the number of crashes per year. This approach has also been implemented in earlier studies on traffic crashes at intersections (Mountain et al. 1998) and motorcycle crashes at intersections (Harnen et al. 2003a, 2003b).

We based the model on the Poisson error structure and used the quasi-likelihood approach (McCullagh and Nelder 1989) to overcome the dispersion problem. A loglinear cross-sectional model was employed with the link function specified as the log (NAG 1994). This approach has been used in earlier studies on motorcycle crashes on highway links (Radin 1996; Radin et al. 1995, 2000) and in our earlier analysis of motorcycle crashes at intersections (Harnen et al. 2003a, 2003b).

Using the quasi-likelihood approach, the dispersion parameter was estimated from the mean deviance (scaled deviance over its degrees of freedom). This may result in a model where the scaled deviance is equal to its degrees of freedom. The final model was based on the goodness-of-fit and significance tests carried out on the models such as the change in scaled deviance from adding or removing the terms, the ratio of scaled deviance to its degrees of freedom (mean deviance), and the 5% significance level of *t*-statistics of the parameter estimates.

Both multivariate and univariate analyses were conducted for Model 1, while only multivariate analysis was undertaken for Model 2. We used multivariate analysis to assess which of the variable(s) had the most effect on the probability of motorcycle crashes. The univariate analysis was employed to obtain a complete picture of the effect of all explanatory variables on motorcycle crashes. It should be noted that only those variables found significant at the 5% level in the univariate analysis were subsequently included in the multivariate analysis.

RESULTS

Model 1

Table 2 presents the results of the univariate analysis for Model 1. It can be seen that all terms, except *QPED*, *LNn*, and *NL*, were significant at the 5% level. The respective scaled deviance was equal to its corresponding degrees of freedom, as the quasi-likelihood approach had been introduced in the fitting process. Because the terms *QPED*, *LNn*, and *NL* were not significant at the 5% level, they were then excluded from any further analysis.

The multivariate analysis (table 3) shows that all explanatory variables were significant at the 5% level. The scaled deviance was equal to its degrees of freedom, changing from 15,022.0 to 39.0 with a loss of 11 degrees of freedom. The mean deviance changed from 300.4 to 1.0.

On the basis of the multivariate analysis, the final model is:

$$
\begin{aligned}
MCA = {} & 0.002822\ QNMm^{0.3241}\ QNMn^{0.0835} \bullet \\
& QMm^{0.0683}\ QMn^{0.1296}\ \mathrm{EXP}^{z} \qquad (5)
\end{aligned}
$$

where

$$
\begin{aligned}
z = {} & 0.02602\ SPEED - 0.0727\ LWm - 0.0718\ LWn \\
& - 0.01758\ LNm - \beta_7 SHDW + \beta_8 LU
\end{aligned}
$$

where *MCA* is motorcycle crashes per year, β_7 = 0.0, 0.01755, and 0.02554 for *SHDW* = 1, 2, and 3, respectively, β_8 = 0.0 and 0.01591 for *LU* = 1

TABLE 1 Description, Factor Levels, Coding System, and Basic Statistics of the Explanatory Variables

Explanatory variables	Description	Factor levels	Coding system in GLIM	Min	Max	Mean	Median
MODEL 1							
QNMm	Nonmotorcycle flow on major road (nmpd)		*QNMm*	14,527	50,529	31,389	32,354
QNMn	Nonmotorcycle flow on minor road (nmpd)		*QNMn*	2,133	20,129	11,276	11,129
QMm	Motorcycle flow on major road (mpd)		*QMm*	5,510	21,899	12,228	10,792
QMn	Motorcycle flow on minor road (mpd)		*QMn*	1,752	4,771	3,183	3,142
QPED	Pedestrian flow(pedestrians/ hour)		*QPED*	0	235	36	19
SPEED	Approach speed (km/hour)		*SPEED*	53.00	68.00	59.57	59.50
LWm	Average lane width on major road (m)		*LWm*	3.30	4.00	3.58	3.60
LWn	Average lane width on minor road (m)		*LWn*	3.40	4.00	3.69	3.60
LNm	Number of lanes on major road (lanes/traffic direction)		*LNm*	2	5	2.6	2.0
LNn	Number of lanes on minor road (lanes/traffic direction)		*LNn*	1	3	1.6	2.0
NL	Number of legs	2	(1) 3-legged (2) 4-legged	1	2	1.5	1.0
SHDW	Average shoulder width on major and minor road	3	(1) *SHDW* = 0.00 m (2) 0.00 < *SHDW* ≤ 1.00 m (3) *SHDW* > 1.00 m	1	3	1.7	2.0
LU	Land-use category	2	(1) Noncommercial area (2) Commercial area	1	2	1.7	2.0
MODEL 2							
Qmajor	Traffic flow on major road (vehicles/day)		*Qmajor*	20,043	72,428	43,617	42,258
Qmajor	Traffic flow on minor road (vehicles/day)		*Qminor*	4,504	24,900	14,459	14,293
SHD	Average shoulder width on major and minor road (m)		*SHD*	0	1.3	0.5	0.9

Key: km = kilometers; m = meters; mpd = motorcycles per day; nmpd = nonmotorcycles per day.

and 2, respectively (table 1). Figure 4 shows the actual and predicted motorcycle crashes.

Model 2

Table 4 presents the results of the multivariate analysis of Model 2. All terms were found to be significant at the 5% level. The scaled deviance was equal to its degrees of freedom, because the quasi-likelihood approach had also been introduced in the fitting process. The scaled deviance changed from 854.8 to 47.0 with a loss of 3 degrees of freedom and the mean deviance changed from 17.1 to 1.0.

TABLE 2 Univariate Analysis of Model 1

Explanatory variables	Estimates	Standard errors	Degrees of freedom	Scaled deviance	*t*-statistics	Sig. at 0.05
Constant	–9.2260	0.3480	49	49	–26.55	Yes
QNMm	0.9835	0.0334			29.42	Yes
Constant	–1.2210	0.2160	49	49	–5.64	Yes
QNMn	0.2490	0.0243			10.26	Yes
Constant	–0.7520	0.2580	49	49	–2.92	Yes
QMm	0.1943	0.0288			6.76	Yes
Constant	–2.0910	0.3790	49	49	–5.51	Yes
QMn	0.3877	0.0478			8.12	Yes
Constant	0.8636	0.0748	49	49	11.54	Yes
QPED	0.0357	0.0237			1.51	No
Constant	–3.6760	0.1090	49	49	–33.63	Yes
SPEED	0.0771	0.0018			42.83	Yes
Constant	3.2900	1.1800	49	49	2.79	Yes
LWm	–0.6510	0.3290			–1.98	Yes
Constant	3.0200	1.0500	49	49	2.88	Yes
LWn	–0.5800	0.2950			–1.97	Yes
Constant	1.1960	0.1260	49	49	9.47	Yes
LNm	–0.1023	0.0519			–1.97	Yes
Constant	1.0780	0.1200	49	49	8.97	Yes
LNn	–0.0744	0.0697			–1.07	No
Constant	1.0020	0.1280	49	49	7.83	Yes
NL (2)	–0.0294	0.0826			–0.36	No
Constant	1.0578	0.0524	48	48	20.17	Yes
SHDW (2)	–0.1812	0.0856			–2.12	Yes
SHDW (3)	–0.2750	0.1190			–2.32	Yes
Constant	0.8316	0.0752	49	49	11.05	Yes
LU (2)	0.1774	0.0885			2.01	Yes

Note: Estimates for factors (2) and (3) are the differences compared with the reference level (1).

The final model developed in this analysis was:

$$(MCA = 0.0004693\ Qmajor^{0.5948} Qminor^{0.2411}) \bullet \text{EXP}^{-0.0589\ SHD} \qquad (6)$$

Tables 2, 3, and 4 show that the variables have a consistent effect on motorcycle crashes. This is indicated by the sign (plus or minus) of the parameter estimates for each of the corresponding variables that are identical.

DISCUSSION

Model 1

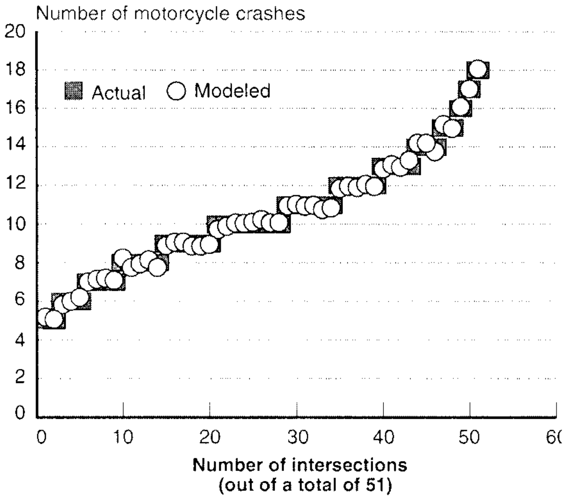
The final Model 1 reveals that the number of motorcycle crashes per year is proportional to the

TABLE 3 Multivariate Analysis of Model 1

Explanatory variables	Estimates	Standard errors	Degrees of freedom	Scaled deviance	*t*-statistics	Sig. at 0.05	Mean deviance
Constant	−5.8700	0.4580	50	15,022.0	−12.81	Yes	300.4
QNMm	0.3241	0.0297	49	748.6	10.91	Yes	15.3
QNMn	0.0835	0.0183	48	483.6	4.57	Yes	10.1
QMm	0.0683	0.0188	47	241.5	3.64	Yes	5.1
QMn	0.1296	0.0230	46	142.8	5.63	Yes	3.1
SPEED	0.0260	0.0033	45	75.1	7.79	Yes	1.7
LWm	−0.0727	0.0320	44	70.7	−2.27	Yes	1.6
LWn	−0.0718	0.0305	43	69.1	−2.35	Yes	1.6
LNm	−0.0176	0.0044	42	55.0	−3.97	Yes	1.3
SHDW (2)	−0.0176	0.0069	40	47.5	−2.55	Yes	1.2
SHDW (3)	−0.0255	0.0100	40	47.5	−2.56	Yes	1.2
LU (2)	0.0159	0.0055	39	39.0	2.91	Yes	1.0

Note: Estimates for factors (2) and (3) are the differences compared with the reference level (1).

FIGURE 4 Actual and Modeled Motorcycle Crashes: 1997–2000 (Model 1)



traffic flow entering the intersection. The estimates of *QNMm*, *QNMn*, *QMm*, and *QMn* indicate that an increase in nonmotorcycle and motorcycle flows on major and minor roads is associated with more motorcycle crashes (figure 5). For instance, doubling nonmotorcycle flow on a major road (*QNMm*) is expected to cause an increase of about 25% in motorcycle crashes. If all traffic entering the intersection is doubled, an increase of about 45% in motorcycle crashes would result. We also found that nonmotorcycle flows on major roads (*QNMm*) was the most important variable for the probability of motorcycle crashes. The results support the findings of earlier studies on traffic crashes at intersections (Summersgill 1991; Mountain et al. 1998; Rodriguez and Sayed 1999; Vogt and Bared 1998; Vogt 1999; Bauer and Harwood 2000).

The *SPEED* estimate shows that an increase in approach speed is associated with a rise in motorcycle crashes. For instance, if the approach speed goes up by 10 kilometers per hour, 30% more motorcycle crashes can be expected. Our findings support earlier studies on the relationship of traffic speed to crashes (Griebe and Nielsen 1996; Vogt and Bared 1998; Bauer and Harwood 2000; Lynam et al. 2001; USDOT 2002; Taylor et al. 2002).

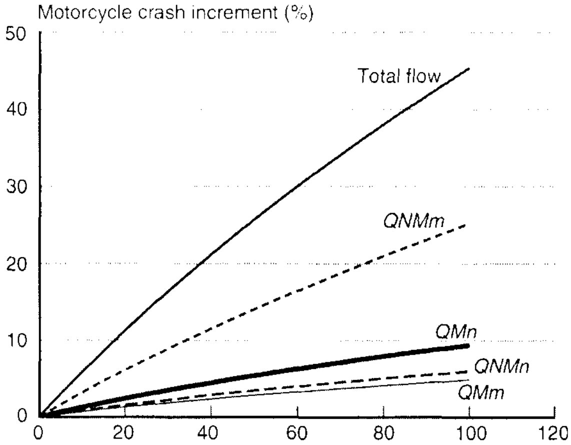
The estimates of *LWm* and *LWn* imply that a wider lane is associated with a reduction in motorcycle crashes. For instance, widening the lane on major and minor roads by 0.50 meters is expected to reduce motorcycle crashes by some 3.6% and 3.5%, respectively. This result is in line with the finding reported in an earlier study on traffic crashes at intersections (Bauer and Harwood 2000).

Meanwhile, the estimate of *LNm* indicates that an increase in the number of lanes on a major road is associated with a reduction in motorcycle crashes. However, the effect of this variable is marginal (1.7%). The result seems to be in line with the finding reported by Bauer and Harwood (2000). This reduction was probably the result of the presence of

TABLE 4 Multivariate Analysis of Model 2

Explanatory variables	Estimates	Standard errors	Degrees of freedom	Scaled deviance	*t*-statistics	Sig. at 0.05	Mean deviance
Constant	–7.6640	0.4650	50	854.8	–16.49	Yes	17.1
Qmajor	0.5948	0.0707	49	65.4	8.41	Yes	1.3
Qminor	0.2411	0.0640	48	52.1	3.77	Yes	1.1
SHD	–0.0589	0.0261	47	47.0	–2.25	Yes	1.0

FIGURE 5 Effects of Traffic Flow on Motorcycle Crashes: Model 1



an exclusive right turn lane on the major road. Of the 51 intersections we studied, 48 had an exclusive right turn lane on each major road approach. The presence of such lanes may reduce rear-end crashes for motorcycles. It should be mentioned that an exclusive turning lane was counted as a lane in our measurements of *LNm*. Earlier studies confirmed the benefit provided by such lanes for crash reduction at intersections (Kulmala 1992; Vogt 1999; Bauer and Harwood 2000) and at links (Tarko et al. 1999). However, for a better explanation, a separate model should be developed to explain the effects of an exclusive left, exclusive right, and short turning lanes on all types of motorcycle crashes at intersections.

The *SHDW* estimates indicate that a wider paved shoulder is associated with fewer motorcycle crashes. The result seems to be in line with the finding reported by Bauer and Harwood (2000). For instance, 25% more motorcycle crashes occur at intersections without a shoulder than at intersections with a shoulder wider than 1.0 meters. When we compare motorcycle crashes at intersections without a shoulder with crashes where the shoulder width is between 0.0 meters and ≤1.0 meters, the difference is smaller, only 1.7% more crashes occur when there is no shoulder. This finding seems reasonable because motorcyclists use the available shoulders width when approaching an intersection, and the rates of rear-end and sideswipe crash types between motorcycles on the shoulder and other vehicles on the adjacent lane should be lower if the shoulder is wider. This situation is common in countries like Malaysia with a high population of motorcycles. However, a better explanation can be provided as a separate model was developed to explain the effect of shoulder width on all types of motorcycle crashes at intersections.

The estimate of *LU* shows that signalized intersections located within commercial areas are associated with increased motorcycle crashes. The result confirms the findings of an earlier study on traffic crashes at four-legged signalized intersections (Wang and Ieda 1997). However, the difference in the estimation of motorcycle crashes between commercial and noncommercial areas is marginal (1.6%). As explained earlier, this study includes only those intersections located within commercial areas having no access road to the adjacent land use within 50 meters of the intersection stop lines. As such, the number of conflicts between vehicles entering or leaving the intersection and vehicles turning into or out of the adjacent land use may be reduced, hence fewer crashes. The effect of access control or the number of accesses on traffic crashes has also been reported in earlier studies (Vogt 1999; Bauer and Harwood 2000).

Model 2

Model 2 results verify the contribution of traffic flow, both on major roads (*Qmajor*) and minor roads (*Qminor*), to motorcycle crashes. The estimates of the variables show that an increase in traffic flow on major and minor roads is associated with a greater number of motorcycle crashes, and an increase in shoulder width (*SHD*) is associated with a reduction in these crashes. For example, widening the shoulder by 1.0 meters is expected to reduce the number of motorcycle crashes by about 6%. In this model, the effect of shoulder width on motorcycle crashes can be directly quantified when the width is changed, and this is one of the main differences between Model 1 and Model 2 .

As described earlier, design curves relating major- and minor-road flows for different shoulder widths can be developed based on Model 2 (figure 6). As discussed, wider shoulder widths at intersections offer higher levels of safety to motorcyclists approaching the junction. Based on the relationships among the variables developed based on Models 1 and 2, future work includes carrying out an indepth analysis of whether intersection treatments that have non-exclusive motorcycle lane facilities could reduce motorcycle crashes.

CONCLUSIONS

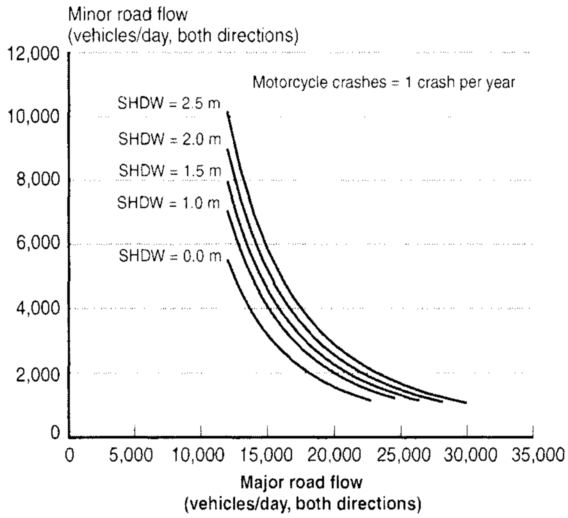
This paper presents motorcycle crash prediction models for signalized intersections on urban roads in Malaysia. The models reveal that traffic flow, approach speed, intersection geometry, and land use are significant factors in explaining motorcycle crashes at signalized intersections. The number of crashes is proportional to the level of traffic entering the intersections. An increase in motorcycle crashes is associated with a larger total vehicle flow on major and minor roads. Nonmotorcycle flows on major roads had the most effect on the likelihood of motorcycle crashes.

An increase in approach speed is associated with more motorcycle crashes, while wider lanes, a greater number of lanes, and wider shoulders bring a reduction in these crashes. Furthermore, more motorcycle crashes occur at signalized intersections located within commercial areas than at intersections located outside of commercial areas.

The models developed in this study present information to aid traffic engineers in deciding the appropriate level of intervention for intersection treatment with respect to motorcycle crashes. Using our models, design parameters for intersections may be changed to achieve appropriate safety levels. Decisions on whether special treatment to minimize motorcycle conflicts is needed at intersections can be objectively carried out based on the models. However, the models might only be valid for a typical traffic environment in developing countries like Malaysia, where the proportion of motorcycles is 20% to 40% of all vehicles at signalized intersections.

For design options, further investigation of the role of parameters of traffic flow by time periods (hourly, peak hour, peak periods) and categorizing the models by time period(s) is suggested, and the need for further categorization of model structure by different intersection geometric configurations (e.g., intersections with and without exclusive motorcycle lanes) is also advised.

FIGURE 6 Relationship of Major- and Minor-Road Flows with Differing Shoulder Widths (based on Model 2)



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