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An analysis of motorcycle injury and vehicle damage severity using ordered probit models

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Abstract

Problem: Motorcycles constitute about 19% of all motorized vehicles in Singapore and are generally overrepresented in traffic accidents, accounting for 40% of total fatalities. *Method*: In this paper, an ordered probit model is used to examine factors that affect the injury severity of motorcycle accidents and the severity of damage to the vehicle for those crashes. Nine years of motorcycle accident data were obtained for Singapore through police reports. These data included categorical assessments of the severity of accidents based on three levels. Damage severity to the vehicle was also assessed and categorized into four levels. Categorical data of this type are best analyzed using ordered probit models because they require no assumptions regarding the ordinality of the dependent variable, which in this case is the severity score. Various models are examined to determine what factors are related to increased injury and damage severity of motorcycle accidents. *Results*: Factors found to lead to increases in the probability of severe injuries include the motorcyclist having non-Singaporean nationality, increased engine capacity, headlight not turned on during daytime, collisions with pedestrians and stationary objects, driving during early morning hours, having a pillion passenger, and when the motorcyclist is determined to be at fault for the accident. Factors leading to increased probability of vehicle damage include some similar factors but also show some differences, such as less damage associated with pedestrian collisions and with female drivers. In addition, it was also found that both injury severity and vehicle damage severity levels are decreasing over time.

Keywords: Motorcyclists; Safety; Accident severity; Damage severity; Ordered probit model

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1. Introduction

Motorcycles represent a substantial portion of the motorized fleet in Singapore, accounting for 19% of all motorized vehicles. They also account for more than their share of total accidents. From 1992 to 2000, motorcycles were involved in 35% of all motor vehicle accidents. Furthermore, motorcycles account for about 40% of total fatal accidents, substantially higher than other types of vehicles. For example, passenger cars, which represent 60% of the fleet, are involved in only about 36% of total fatal accidents. These figures suggest that motorcycling is more prone to fatal accidents than other vehicles.

Safety programs and campaigns are one policy response to reduce motorcycle fatalities. However, these programs have not been targeted at specific issues or causes due to inadequate information on why these accidents are more likely to result in a fatality. While there is a substantial body of work relating to motorcycle safety in western countries, there are very few studies involving such research in Singapore or other rapidly developing economies.

Most previous research on motorcycle accident severity has focused on helmet-related issues such as patterns of head injuries and effectiveness of helmets in reducing both fatalities and the severity of head injury (Branas & Knudson, 2001; Evans & Frick, 1986; Gabella, Reiner, et al., 1995; McKnight & McKnight, 1995; Waston, Zador, & Wilks, 1980; Weiss, 1992). These studies have found positive associations between head injuries and the lack of helmets. Gabella et al. (1995) also examined the relationship between head injury and alcohol use, motorcycle speed, and the individual characteristics of the crash and of the motorcyclists. Due to the tough enforcement of laws on mandatory helmet use in Singapore, all riders including pillion passengers generally use helmets throughout their trip. Therefore, the nonuse of helmets is not relevant in Singapore.

A number of other studies (Mannering & Grodsky, 1995; Rutter & Quine, 1996) examined the effect of the observed characteristics of the individual (e.g., age, gender, and driver experience) on motorcycle accident severity. Rutter and Quine (1996) found that there is a higher casualty rate among middle-aged riders compared to those who are inexperienced. Accidents are also associated with a greater willingness to break the law and violate safe riding rules. Shankar and Mannering (1996) investigated various factors such as alcohol-impaired riding, speeding, rider inattention, roadway type, road surface, and rider age to uncover factors affecting the severity of single-vehicle motorcycle accidents. Langley, Mullin, Jackson, and Norton (2000) attempted to determine the relationship between the cubic capacity of motorcycle engines and the risk of accidents and found that the risk of an injury crash increases with increasing engine capacity of the motorcycle. However, this study ignored the effects of other important variables. Unfortunately, very few studies have attempted to investigate time-series effects within the data to determine if motorcycle accident severity levels are decreasing over time. Some other factors (e.g., the presence of a pillion passenger, headlight condition, type of accident, the presence of surveillance cameras, time of the day, day of the week, and nationality of motorcyclists[1]) that may affect accident severity are often overlooked in the literature.

[1] Due to geographical proximity, a large number of motorcyclists come from Malaysia to work in Singapore everyday.

It is not surprising that some of these issues have not been considered when these studies are conducted in western countries. For example, pillion passengers are very uncommon in these countries, and in the United States, traffic surveillance cameras are very rare. The nature of motorcycle use may also be quite different in the west where motorcycles are used more for recreational travel as opposed to commuting or utilitarian travel.

While previous studies have attempted to evaluate the factors that affect injury severity, none have examined factors affecting the severity of damage to the motorcycle. Motorcycles may experience numerous types of damage when they are involved in an accident and the factors affecting this may differ from those that result in more severe injuries.

Another important element of studying these factors is the selection of appropriate statistical techniques. Most previous research on motorcycle safety has used univariate or bivariate accident severity measures that provide no distinction between the levels of severity. The analyses conducted here uses multivariate modeling, allowing the determination of how multiple factors affect the severity of injury and damage to the vehicle, as well as the relative importance of the effects. In employing multivariate models in what may be its first application to motorcycle accident severity studies, Goldstein (1986) employed a tobit model to investigate head, neck, and body injuries and Weiss (1992) employed the ordered probit model to examine the severity of head injuries. Multinomial logit models were also used to examine motorcycle accident severity and perceived accident risk (Mannering & Grodsky, 1995; Shankar & Mannering, 1996). Duncan, Khattak, and Council (1998), Long (1997), and O'Donnell and Connor (1996) stated that ordered discrete-choice modeling is needed when using categorical dependent variables.

This paper describes the use of an ordered probit model to explain how variations in the characteristics of the roadway, the rider, environmental factors, and the motorcycle can lead to variations in different levels of injury severity and damage to the motorcycle. This study also examines whether factors affecting motorcycle injury severity and vehicle damage severity are identical. Specifically, the models include significant detail on the type of road, the engineering characteristics of the road, the type of collision that occurred, the type of motorcycle, and the demographics of the rider. Time-series effects are also examined. Much of the analyses is exploratory as there are few preconceptions on what factors affect overall severity levels. However, one hypothesis is the expectation that those roads that have a higher degree of engineering standards (i.e., straighter, fewer conflicts, and fewer distractions for the driver) have lower levels of severity. Younger drivers are also expected to have more severe crashes and overall severity is expected to diminish over time.

2. Model specification

The ordered probit model is suitable for models with a categorical dependent variable. Unordered multinomial or nested logit or probit models, while accounting for the categorical nature of the dependent variable, do not account for the ordinal nature of the injury categories (Duncan et al., 1998). The multinomial logit model is also associated with undesirable properties, such as the independence of irrelevant alternatives (Ben-Akiva & Lerman, 1985) and lack of a closed-form likelihood in the case of multinomial probit (Greene, 2000). Although the ordered logit is also suitable for these types of models, the ordered probit model is selected because both formulations give very similar results.

The ordered probit model is usually motivated in a latent (i.e., unobserved) variables framework. The general specification[2] is:

$$y_i{}^* = \boldsymbol{X}_i\boldsymbol{\beta} + \varepsilon_i \tag{1}$$

where $y_i{}^*$ is a latent variable measuring the injury severity of the ith accident or damage severity of the ith motorcycle; $\boldsymbol{X}_i$ is a $(k \times 1)$ vector of observed nonrandom explanatory variables; $\boldsymbol{\beta}$ is a $(k \times 1)$ vector of unknown parameters; ε_i is the random error term, which is assumed to be normally distributed with zero mean and unit variance.

In any given accident, it is reasonable to expect that a high risk of injury or severe damage to the motorcycle, $y_i{}^*$, will be translated into a high level of observed injury or observed damage, y_i. Therefore, the observed and coded discrete injury severity or damage severity variable, y_i is determined from the model as follows:

$$y_i = \begin{cases} 1 \text{ if } -\infty \le y_i{}^* \le \mu_1 & \text{(slight injury accident or no damage to the motorcycle)} \\ 2 \text{ if } \mu_1 \le y_i{}^* \le \mu_2 & \text{(serious injury accident or slight damage to the motorcycle)} \\ 3 \text{ if } \mu_2 \le y_i{}^* \le \mu_3 & \text{(fatal accident or extensive damage to the motorcycle)} \\ 4 \text{ if } \mu_3 \le y_i{}^* \le \infty & \text{(total wreck to the motorcycle)} \end{cases} \tag{2}$$

where the threshold values μ_1, μ_2, and μ_3 are unknown parameters to be estimated.

The parameters of the model are estimated by the method of maximum likelihood (Long, 1997). This method is used for estimation of various motorcycle injury severity and motorcycle damage severity models. The former is estimated with three levels, while four levels were defined for the latter.

In Eq. (1), the partial change in y^* with respect to X_k is β_k. This implies that for a unit change in X_k, y^* is expected to change by β_k units, holding all other variables constant. Since the variance of y^* cannot be estimated from the observed data, the meaning of β_k units in y^* is unclear. McKelvey and Zavoina (1975) suggested that the interpretation should be based on fully standardized continuous variables and y^* should be standardized for other independent variables.

If σ_{y^*} is the unconditional standard deviation of the unobserved y^*, then the y^* standardized coefficient for X_k is:

$$\beta_k^{Sy^*} = \frac{\beta_k}{\sigma_{y^*}} \tag{3}$$

This means that for a unit change in X_k, y^* is expected to change by $\beta_k^{Sy^*}$ standard deviations, holding all other variables constant.

[2] See Long (1997) for a detailed description of the model.

If σ_k is the standard deviation of X_k, then the fully standardized coefficient is:

$$\beta_k^{\mathrm{S}} = \frac{\sigma_k \beta_k}{\sigma_{y^*}} = \sigma_k \beta_k^{\mathrm{S}y^*} \tag{4}$$

where for a unit change in X_k, y^* is expected to increase by β_k^{S} standard deviations, holding all other variables constant.

The variance of y^* can be estimated using the quadratic form:

$$\hat{\sigma}^2_{y^*} = \hat{\boldsymbol{\beta}}\mathrm{Var}(\mathbf{X})\,\hat{\boldsymbol{\beta}}' + \mathrm{Var}(\varepsilon) \tag{5}$$

where Var(**X**) is the covariance matrix for the **X**'s computed from the observed data. For the ordered probit model, $\mathrm{Var}(\varepsilon) = 1$.

With the data analyzed here, it was found that the standard deviation for motorcycle injury severity was 1.40 and for vehicle damage severity was 1.26. These are used to normalize the coefficient estimates. Both unstandardized and standardized coefficient estimates are presented (see Table 3).

The predicted probability of the type of injury severity or damage severity, m, for given $\boldsymbol{X}_i$ is:

$$\hat{P}r(y = m \mid \boldsymbol{X}_i) = F(\hat{\mu}_m - \boldsymbol{X}_i\hat{\boldsymbol{\beta}}) - F(\hat{\mu}_{m-1} - X_i\hat{\boldsymbol{\beta}}) \tag{6}$$

Calculation of these probabilities allows a better understanding of the relative effectiveness of the independent variables. For example, some factors may be more likely to reduce the probability of a fatality and increase injuries, while others may be more effective at reducing injuries. These results are calculated and discussed in section 4.

3. Data

The Traffic Police Department (TP) is responsible for maintaining and disseminating statistics on road traffic accidents in Singapore. Accident data for the years 1992 to 2000 were obtained from TP. A large database of 27,570 accidents involving motorcycles was extracted from these data and used in this study. Two dependent variables are of interest. One is the severity of injuries associated with motorcycle accidents based on three categorical levels: (a) fatal, (b) seriously injured, and (c) slightly injured. For these motorcycle accidents, 3.4% are classified as fatal, 6.2% are classified as seriously injured, and 90.4% are classified as slightly injured. In cases where an injury may have occurred to a pedestrian or car occupant, the accident is classified according to the most severe form of injury. This limitation also means that the impact of these accidents cannot be assessed only on the motorcyclist, but rather on the greatest level of severity of all those involved in the motorcycle accident.

Table 1 summarizes the results for each year. While total motorcycle accidents have increased from 2,803 in 1992 to 3,921 in 2000, the level of severity of those accidents shows a slight downward trend. The total number of fatal accidents each year is relatively constant with an average of 105 fatalities per year.

Table 1
Classification of motorcycle injury and damage severity by year: number and percent of ordered variables

Year	Fatalities	Serious injuries	Slight injuries	Total wreck	Extensive damage	Slight or no damage	Total motorcycle accidents
1992	103	226	2,474	33	531	2,239	2,803
	3.67%	8.06%	88.26%	1.18%	18.94%	79.88%	
1993	117	207	2,697	20	540	2,461	3,021
	3.87%	6.85%	89.28%	0.66%	17.87%	81.46%	
1994	124	194	2,448	12	488	2,266	2,766
	4.48%	7.01%	88.50%	0.43%	17.64%	81.92%	
1995	107	205	2,400	5	520	2,187	2,712
	3.95%	7.56%	88.50%	0.18%	19.17%	80.64%	
1996	99	210	2,753	20	567	2,475	3,062
	3.23%	6.86%	89.91%	0.65%	18.52%	80.83%	
1997	108	147	2,664	23	515	2,381	2,919
	3.70%	5.04%	91.26%	0.79%	17.64%	81.57%	
1998	97	134	2,639	17	394	2,459	2,870
	3.38%	4.67%	91.95%	0.59%	13.73%	85.68%	
1999	87	198	3,210	29	497	2,969	3,495
	2.49%	5.67%	91.85%	0.83%	14.22%	84.95%	
2000	100	198	3,623	28	527	3,366	3,921
	2.55%	5.05%	92.40%	0.71%	13.44%	85.85%	

The other dependent variable is the severity of damage to the motorcycle based on four categorical levels: (a) total wreck, (b) extensive damage, (c) slight damage, and (d) no damage. Over the 9 years of available data, 0.7% of the motorcycles were classified as

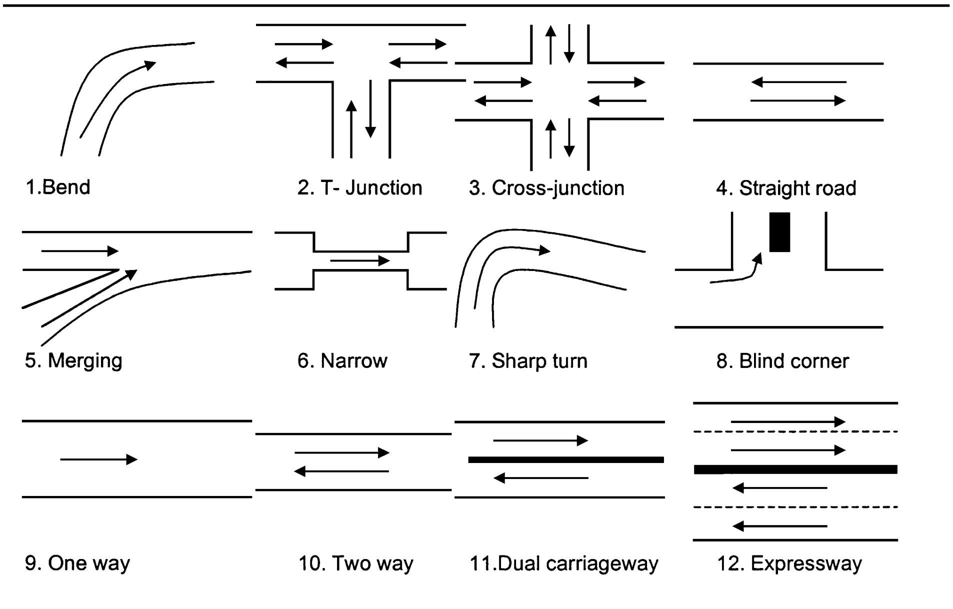

Fig. 1. Typical roadway location, road engineering, and type of traffic.

Table 2
Explanatory variables included in the models

Explanatory variables	Description of the variables	Mean	Standard deviation
Time trend	Month of accident (Assuming that January 1992 = 1 to December 2000 = 108)		
Time of the day			
00:00 a.m. to 3:59 a.m.	If accident happened during this time = 1, otherwise = 0	0.085	0.278
4:00 a.m. to 7:59 a.m.	If accident happened during this time = 1, otherwise = 0	0.115	0.319
8:00 a.m. to 11:59 a.m.	If accident happened during this time = 1, otherwise = 0	0.188	0.39
12:00 noon to 3:59 p.m.	If accident happened during this time = 1, otherwise = 0	0.174	0.379
4:00 p.m. to 7:59 p.m.	If accident happened during this time = 1, otherwise = 0	0.239	0.427
8:00 p.m. to 11:59 p.m.	If accident happened during this time = 1, otherwise = 0	0.198	0.398
Seasonal effects			
January	If accident in January = 1, otherwise = 0	0.081	0.274
February	If accident in February = 1, otherwise = 0	0.076	0.266
March	If accident in March = 1, otherwise = 0	0.087	0.282
April	If accident in April = 1, otherwise = 0	0.082	0.275
May	If accident in May = 1, otherwise = 0	0.081	0.273
June	If accident in June = 1, otherwise = 0	0.082	0.274
July	If accident in July = 1, otherwise = 0	0.089	0.284
August	If accident in August = 1, otherwise = 0	0.085	0.279
September	If accident in September = 1, otherwise = 0	0.082	0.275
October	If accident in October = 1, otherwise = 0	0.088	0.284
November	If accident in November = 1, otherwise = 0	0.079	0.27
December	If accident in December = 1, otherwise = 0	0.085	0.279
Daytime indicator	If accident between 0700 to 1900 = 1, otherwise = 0	0.608	0.488
Weekend	If accident is on Saturday and Sunday = 1, otherwise = 0	0.277	0.448
Type of location			
Bend	If accident on bend = 1, otherwise = 0	0.071	0.257
T-junction	If accident on T-junction = 1, otherwise = 0	0.169	0.375
Cross-junction	If accident on cross-junction = 1, otherwise = 0	0.163	0.37
Straight	If accident on straight road = 1, otherwise = 0	0.495	0.49
Other location	If accident at other location = 1, otherwise = 0	0.092	0.289
Road engineering			
Merging	If accident on merging lane = 1, otherwise = 0	0.007	0.085
Narrow	If accident on narrow lane = 1, otherwise = 0	0.007	0.084
Sharp turn	If accident on sharp turn = 1, otherwise = 0	0.014	0.117
Blind corner	If accident on blind corner = 1, otherwise = 0	0.005	0.074
Others	If accident at other location = 1, otherwise = 0	0.966	0.181
Type of traffic			
One-way	If accident on one-way road = 1, otherwise = 0	0.116	0.32
Two-way	If accident on two-way road = 1, otherwise = 0	0.256	0.436
Dual carriageway	If accident on dual carriageway = 1, otherwise = 0	0.451	0.498
Expressway	If accident on expressway = 1, otherwise = 0	0.178	0.382

(continued on next page)

Table 2 (*continued*)

Explanatory variables	Description of the variables	Mean	Standard deviation
Type of road			
Side road	If accident on side road = 1, otherwise = 0	0.088	0.284
Main road	If accident on main road = 1, otherwise = 0	0.727	0.445
Expressway	If accident on expressway = 1, otherwise = 0	0.184	0.388
Speed limit			
< 40	If speed limit < 40 km/h = 1, otherwise = 0	0.017	0.127
40	If speed limit = 40 km/h = 1, otherwise = 0	0.011	0.106
50	If speed limit = 50 km/h = 1, otherwise = 0	0.746	0.435
70	If speed limit = 70 km/h = 1, otherwise = 0	0.067	0.249
80	If speed limit = 80 km/h = 1, otherwise = 0	0.159	0.365
Nature of lane			
Single lane	If accident in single lane = 1, otherwise = 0	0.112	0.315
Outermost	If accident in outermost lane = 1, otherwise = 0	0.136	0.343
Outer	If accident in outer lane = 1, otherwise = 0	0.122	0.327
Center	If accident in center lane = 1, otherwise = 0	0.251	0.433
Inner	If accident in inner lane = 1, otherwise = 0	0.177	0.381
Innermost	If accident in innermost lane = 1, otherwise = 0	0.201	0.401
Surveillance camera	If surveillance camera exists at accident location = 1, otherwise = 0	0.033	0.179
Road surface			
Dry	If accident on dry surface = 1, otherwise = 0	0.861	0.346
Wet	If accident on wet surface = 1, otherwise = 0	0.124	0.329
Oily	If accident on oily surface = 1, otherwise = 0	0.006	0.074
Sandy	If accident on sandy surface = 1, otherwise = 0	0.009	0.096
Collision type			
Vehicles	If motorcycle collided with vehicles = 1, otherwise = 0	0.682	0.465
Stationary object	If motorcycle collided with stationary object = 1, otherwise = 0	0.061	0.239
Pedestrians	If motorcycle collided with pedestrian = 1, otherwise = 0	0.052	0.222
Single	If single vehicle collision = 1, otherwise = 0	0.204	0.403
Nationality	If the rider is Singaporean = 1, otherwise = 0	0.81	0.39
Engine capacity	Motorcycle cylinder capacity	170.29	133.32
Capacity^2	(Motorcycle cylinder capacity)^2	0.00047	0.0013
Offending	Motorcycle was likely to be an offending party = 1, otherwise = 0	0.587	0.492
Headlight	If headlight is on at daylight = 1, otherwise = 0	0.359	0.48
Rider age	Motorcyclist age in years	30.01	11.40
Age	(Motorcyclist age in years)	1029.36	872.5
Age cohorts			
Less 20	If rider age is < 20 years = 1, otherwise = 0	0.107	0.308
Age 20–29	If rider age within 20–29 = 1, otherwise = 0	0.511	0.499
Age 30–39	If rider age within 30–39 = 1, otherwise = 0	0.198	0.399
Age 40–49	If rider age within 40–49 = 1, otherwise = 0	0.102	0.304
Age 50–59	If rider age is 50–59 = 1, otherwise = 0	0.052	0.224
Age 60–69	If rider age is 60–69 = 1, otherwise = 0	0.024	0.152
Age 70 or more	If rider age is 70 or more = 1, otherwise = 0	0.004	0.063
Pillion passenger	If there is pillion passenger = 1, otherwise = 0	0.198	0.398
Gender	If rider is male = 1, otherwise = 0	0.016	0.125

total wrecks, 16.6% with extensive damage, 79.9% with slight damage, and only 2.8% with no damage. Damage severity also appears to decrease over time.

Each observation in the data set is associated with one motorcycle crash. In addition to injury and vehicle severity levels, a record of the roadway, rider, environmental, and motorcycle characteristics was also recorded. The coded information for each observation contains up to 70 variables. From these data, 20 variables were chosen that were hypothesized to have some association with the severity levels. Typical geometric layouts analyzed in the data are defined and shown in Fig. 1. The definition of the variables, which were obtained from a coding manual supplied with the data set by TP, together with each variable's mean and standard deviation, is presented in Table 2. The majority of these variables are categorical dummy variables that simply indicate the existence of a certain condition such as the road type at the accident location.

4. Estimation results

The parameters of the ordered probit model were estimated by maximum likelihood estimation. Estimation results are shown in Table 3 for both a model of injury severity and motorcycle damage severity. Both unstandardized and standardized coefficient estimates are shown, as discussed previously. A goodness-of-fit statistic, the adjusted log likelihood index ratio[3] ($\bar{\rho}^2$), is also presented in Table 3 for all models. The main focus of this discussion is on the *t* statistics, which reflects the statistical significance of the independent variables. The changes in the probability levels of the dependent variables are also estimated, which provides an interpretation of the substantive effect of the independent variables. These are measured relative to a reference case where all the dummy variables are set equal to 0, the time trend is set to January 1992, and the engine capacity is set to 170.29 cc, which is the average value in the data set (see Tables 4 and 5). This allows one to interpret changes in the probability of the severity levels for a change in a given parameter, relative to the reference case.

A time trend variable representing the month in which the accident occurred is included in the model. This has a negative and significant coefficient indicating that some factor that varies over time is leading to a downward trend in both injury and damage severities. Table 1 shows the reduction in the severity and damage levels over time. While the trend shows some variation, there does appear to be a downward trend in the percentage of accidents resulting in a fatality. Extensive damage to the motorcycle also shows a downward trend. These results suggest that, all else equal, some other unmeasured factor is having an influence on the relative severity of motorcycle accidents.

The changes in probability values for the time trend show a very interesting result. First, the probability of a fatality drops from 1.02% in the reference case to only 0.58% in December 2000. In other words, the effect of time alone reduces fatal outcomes by over 40%. Serious injuries are also reduced from 2.9% to 1.9% of accidents (or by 34%). In contrast, damage to the motorcycle shows that about 5% fewer accidents result in no damage (16.07% reduced to 15.25%) while slight and extensive damage both increase, the

[3] See Ben-Akiva and Lerman (1985) for a detailed description of this statistic.

Table 3
Ordered probit estimates for motorcycle injury and motorcycle damage severity

Variables	Motorcycle injury severity			Motorcycle damage severity		
	β	β^{S_y*}	t statistic	β	β^{S_y*}	t statistic
Time trend	− 0.0019	− 0.0014	− 5.16	− 0.0014	− 0.0001	− 4.88
Weekend	0.039	0.028	1.67	0.024	0.019	1.31
Time of day						
12:00 midnight to 3:59 a.m.	0.299	0.214	7.68	0.203	0.161	6.19
4.00 a.m. to 7:59 a.m.	0.084	0.06	2.17	0.017	0.013	0.55
8.00 a.m. to 11:59 a.m.	− 0.138	− 0.098	− 3.61	− 0.115	− 0.091	− 3.98
12:00 noon to 3:59 p.m.	− 0.097	− 0.069	− 2.55	− 0.066	− 0.052	− 2.28
4:00 p.m. to 7:59 p.m.	− 0.056	− 0.04	− 1.65	− 0.072	− 0.057	− 2.71
Seasonal effects						
February	− 0.037	− 0.026	− 0.71	− 0.067	− 0.053	− 1.65
March	0.026	0.019	0.53	− 0.015	− 0.012	− 0.38
April	− 0.009	− 0.006	− 0.18	0.019	0.015	0.48
May	− 0.07	− 0.05	− 1.34	− 0.006	− 0.005	− 0.15
June	− 0.006	− 0.004	− 0.12	0.005	0.004	0.13
July	− 0.08	− 0.057	− 1.56	− 0.025	− 0.019	− 0.64
August	0.009	0.006	0.19	0.011	0.009	0.27
September	− 0.004	− 0.003	− 0.09	− 0.007	− 0.005	− 0.17
October	− 0.007	− 0.005	− 0.14	− 0.006	− 0.005	− 0.17
November	− 0.071	− 0.05	− 1.35	− 0.012	− 0.01	− 0.54
December	− 0.07	− 0.05	− 1.33	0.027	0.021	0.68
Type of location (relative to "other")						
Bend	0.211	0.151	4.15	0.124	0.098	2.98
T-junction	0.0012	0.0009	0.03	0.113	0.089	3.21
Cross-junction	0.064	0.046	1.36	0.231	0.183	6.41
Straight	− 0.058	− 0.041	− 1.47	− 0.071	− 0.056	− 2.39
Road engineering (relative to "other")						
Merging	− 0.089	− 0.064	− 0.69	− 0.18	− 0.143	− 1.86
Narrow	− 0.002	− 0.001	− 0.10	− 0.076	− 0.066	− 0.76
Sharp turn	− 0.009	− 0.006	− 0.11	0.245	0.194	3.48
Blind corner	0.097	0.069	0.75	0.096	0.076	0.87
Type of traffic (relative to one-way)						
Two-way	0.205	0.146	4.79	0.202	0.16	6.57
Dual carriage	0.277	0.198	7.00	0.239	0.189	8.33
Expressway	0.357	0.255	7.99	0.226	0.179	7.27
Nature of lane (relative to single lane)						
Outermost	0.236	0.169	4.84	0.144	0.114	4.02
Outer	0.221	0.158	4.59	0.131	0.104	3.68
Center	0.122	0.087	2.64	0.139	0.11	4.23
Inner	0.134	0.096	2.89	0.004	0.003	0.11
Innermost	0.151	0.108	3.30	0.048	0.038	1.44
Surveillance camera	0.098	0.07	1.73	0.208	0.165	4.75
Road surface (wet)	− 0.089	− 0.064	− 2.41	− 0.055	− 0.044	− 2.15
Motorcycle collided with (relative to collided with no object)						
Vehicles	0.199	0.142	6.08	0.485	0.385	19.47
Stationary object	0.759	0.542	18.05	0.535	0.425	14.10
Pedestrians	0.611	0.436	12.37	− 0.378	− 0.03	− 8.80
Nationality	− 0.163	− 0.116	− 6.01	− 0.003	− 0.002	− 0.14
Engine capacity	0.00034	0.0002	4.49	0.00028	0.0002	4.6

Table 3 (*continued*)

Variables	Motorcycle injury severity			Motorcycle damage severity		
	β	β^{S_y*}	*t* statistic	β	β^{S_y*}	*t* statistic
Offending	0.11	0.078	4.59	0.018	0.014	1.00
Headlight at daytime	− 0.085	− 0.061	− 3.01	− 0.057	− 0.045	− 2.69
Age groups						
Less than 20	0.059	0.042	0.33	0.268	0.213	2.08
20–29	0.023	0.016	0.13	0.217	0.172	1.70
30–39	− 0.018	− 0.013	− 0.10	0.106	0.084	0.83
40–49	− 0.025	− 0.018	− 0.14	0.031	0.025	0.24
50–59	0.103	0.074	0.57	− 0.06	− 0.048	− 0.46
60–69	0.295	0.21	1.58	− 0.039	− 0.03	− 0.29
Gender (male = 1)	− 0.003	− 0.0021	− 2.40	0.189	0.15	2.82
Pillion passenger	0.131	0.094	5.12	− 0.04	− 0.032	− 2.06
Ancillary parameters						
μ_1	1.817			− 1.125		
μ_2	2.376			1.936		
μ_3				3.538		
Log likelihood	− 9927.81			− 15,802.78		
$\bar{\rho}^2$	0.053			0.063		
Total observations	27,552			27,552		

latter by 8%. Given that other factors that affect the severity of both injury outcomes and motorcycle damage are controlled for, these changes over time are likely due to some other exogenous factor. Noland (in press) found that improvements in medical technology have had a significant effect in reducing fatal accidents, which might be one source of this time trend effect.

Time of day effects in the model are measured with dummy variables for 4-h time intervals, usually in the late evening (8:00 p.m. to midnight). Relative to this reference time period, more severe injuries occur in the early morning periods and less severe injuries occur during the day. Early morning (midnight to 3:59 a.m.) fatality probabilities are 112% higher. A similar pattern is apparent for damage to the motorcycle. This is not surprising as it is likely that speeds and alcohol use are greater at these hours, both of which were not controlled for in these data but could lead to more severe injuries and damage. Accidents on weekends (relative to weekdays) also have a positive coefficient and about a 10% increase in fatalities. The probability of extensive damage increases by 5.5% and for total wrecks by 9.3%.

Seasonal effects were measured using monthly dummy variables. No variation is found but this is due to the lack of seasonal climatic variation in Singapore, which sits near the equator. Probabilities for these effects were not calculated due to their lack of statistical significance.

Three general categories of road engineering and design features were examined: (a) type of location, (b) engineering features, and (c) type of traffic separation. These are illustrated schematically in Fig. 1.

The type of location is measured relative to “other” features, which represent a collection of locations with relatively few accidents in the data set. These include bridges,

Table 4
Motorcycle injury severity probabilities

	Estimated probability			Percent change relative to reference case (%)		
	Slight injury	Serious injury	Fatal	Slight injury	Serious injury	Fatal
Reference case	0.9609	0.029	0.0102			
Accident in December 2000	0.9751	0.019	0.0058	1.48	– 34.48	– 43.14
Accident on weekend	0.9574	0.0313	0.0113	– 0.36	7.93	10.78
Time of day						
12:00 a.m. to 3:59 a.m.	0.9281	0.0503	0.0217	– 3.42	73.37	112.37
4:00 a.m. to 7:59 a.m.	0.9532	0.0341	0.0127	– 0.80	17.68	24.40
8:00 a.m. to 11:59 a.m.	0.9712	0.0218	0.0070	1.07	– 24.77	– 31.44
12:00 p.m. to 3:59 p.m.	0.9684	0.0238	0.0078	0.78	– 18.08	– 23.33
4:00 p.m. to 7:59 p.m.	0.9654	0.0258	0.0087	0.47	– 10.89	– 14.30
Type of location						
Bend	0.9393	0.0432	0.0175	– 2.25	48.97	71.57
T-junction	0.9608	0.029	0.0102	– 0.01	0.00	0.00
Cross-junction	0.9551	0.0329	0.0121	– 0.60	13.45	18.63
Straight road	0.9655	0.0258	0.0087	0.48	– 11.03	– 14.71
Road engineering						
Merging	0.9679	0.0242	0.0080	0.72	– 16.71	– 21.63
Narrow	0.9611	0.0288	0.0101	0.02	– 0.61	– 0.90
Sharp turn	0.9617	0.0284	0.0099	0.08	– 2.02	– 2.78
Blind corner	0.9518	0.0350	0.0131	– 0.94	20.75	28.81
Type of traffic						
Two-way	0.9401	0.0427	0.0172	– 2.16	47.24	68.63
Dual carriageway	0.9311	0.0484	0.0205	– 3.10	66.90	100.98
Expressway	0.9197	0.0554	0.0249	– 4.29	91.03	144.12
Nature of lane						
Outermost	0.9364	0.045	0.0186	– 2.55	55.17	82.35
Outer	0.9381	0.0439	0.0179	– 2.37	51.38	75.49
Center	0.9494	0.0366	0.014	– 1.20	26.21	37.25
Inner	0.9481	0.0375	0.0144	– 1.33	29.31	41.18
Innermost	0.9463	0.0387	0.0151	– 1.52	33.45	48.04
Surveillance camera	0.9518	0.035	0.0131	– 0.95	20.69	28.43
Wet road surface	0.9675	0.0244	0.0081	0.69	– 15.86	– 20.59
Collision type						
Vehicles	0.9408	0.0422	0.017	– 2.09	45.52	66.67
Stationary object	0.8419	0.0989	0.0592	– 12.38	241.03	480.39
Pedestrians	0.875	0.0813	0.0437	– 8.94	180.34	328.43
Nationality	0.9728	0.0206	0.0065	1.24	– 28.97	– 36.27
Engine capacity max (1500 cc)	0.9049	0.0643	0.0308	– 5.83	121.72	201.96
Motorcyclist was offender	0.9506	0.0358	0.0136	– 1.07	23.45	33.33
Headlight on during daytime	0.9675	0.0244	0.0081	0.69	– 15.90	– 20.62
Age cohorts						
Less than 20	0.9556	0.0325	0.0119	– 0.55	12.07	16.67
Age 20–29	0.9589	0.0303	0.0108	– 0.21	4.48	5.88

Table 4 (*continued*)

	Estimated probability			Percent change relative to reference case (%)		
	Slight injury	Serious injury	Fatal	Slight injury	Serious injury	Fatal
Age cohorts						
Age 30–39	0.9623	0.028	0.0097	0.15	− 3.45	− 4.90
Age 40–49	0.9629	0.0276	0.0095	0.21	− 4.83	− 6.86
Age 50–59	0.9513	0.0354	0.0133	− 1.00	22.07	30.39
Age 60–69	0.9287	0.0499	0.0214	− 3.35	72.07	109.80
Gender (male)	0.9611	0.0288	0.0101	0.02	− 0.69	− 0.98
With pillion passenger	0.9484	0.0373	0.0143	− 1.30	28.62	40.20

flyovers, slip roads, and tunnels, among others. Of the features specifically included in the estimates, bends in the road appear to result in more severe injuries while t-junctions, cross-junctions, and straight roads do not show a significant difference from the "other" categories. Accidents at bends in the road may result in motorcyclists leaving the travel lanes and overturning or striking an off-road object such as a guardrail, rocks, or trees. The probability of a fatality increases by 71.6% for this type of accident. Interestingly, while the coefficient for cross-junctions was not statistically significant, accidents at these locations still have an 18.6% increase in the probability of a fatality, relative to this reference case.

With regard to damage to the motorcycle, all the location types show a significant effect with cross-junctions resulting in the highest probability of increases in "total wreck." Accidents on straight roads appear, however, to result in less damage to the motorcycle relative to "other" locations (with a decreased probability of 23.7% in the accident resulting in a "total wreck"). Accidents at cross-junctions may result in the motorcycle colliding with a heavy vehicle or may result in multivehicle collisions that cause greater damage to the vehicle.

The road engineering categories include whether the accident occurred at a merge, a narrow road, a sharp turn, or a blind corner. These are estimated relative to an undesignated "other" as marked on the TP Accident Data Form. These factors do not show any statistical significance with respect to injury severity levels. Accidents in merging lanes, however, appear to reduce the severity of damage to the motorcycle (at a 90% significance level) and accidents at sharp turns increase damage levels. This is also reflected in the magnitude of the changes in probabilities.

The type of traffic on the road is measured relative to one-way traffic. In all cases, it is found that two-way streets, dual carriageways, and expressways lead to more severe injuries and more severe damage to the motorcycle. The standardized coefficients for the injury severity model increases with the design standards of the roadway. Two-way streets, which have no median, have a standardized coefficient of 0.146; dual carriageways, which have a median, have a standardized coefficient of 0.198; while expressways have a coefficient value of 0.255. The relative increase in probabilities of a fatality occurring shows a similar pattern. This finding is consistent with results by Shankar and Mannering (1996). Clearly, the increased speed allowed on the higher standard roads may be a factor in increasing injury severity.

Table 5
Motorcycle damage severity probabilities

Name of the attributes	Estimated probability				Percent change relative to reference case (%)			
	No damage	Slight damage	Extensive damage	Total wreck	No damage	Slight damage	Extensive damage	Total wreck
Reference case	0.1206	0.8500	0.0291	0.0002				
Accident in December 2000	0.1525	0.8266	0.0207	0.0001	26.46	− 2.75	− 28.87	− 42.76
Accident on weekend	0.1159	0.8531	0.0308	0.0003	− 3.91	0.36	5.51	9.30
Time of day								
12:00 a.m. to 3:59 a.m.	0.0846	0.8696	0.0453	0.0005	− 29.82	2.30	55.31	109.39
4:00 a.m. to 7:59 a.m.	0.1172	0.8523	0.0303	0.0003	− 2.81	0.26	3.93	6.59
8:00 a.m. to 11:59 a.m.	0.1452	0.8323	0.0224	0.0002	20.37	− 2.08	− 23.31	− 35.29
12:00 p.m. to 3:59 p.m.	0.1344	0.8404	0.0251	0.0002	11.41	− 1.13	− 14.04	− 22.03
4:00 p.m. to 7:59 p.m.	0.1356	0.8395	0.0247	0.0002	12.43	− 1.24	− 15.17	− 23.74
Type of location								
Bend	0.0975	0.8638	0.0383	0.0004	− 19.15	1.62	31.47	57.86
T-junction	0.0994	0.8628	0.0374	0.0004	− 17.59	1.51	28.43	51.77
Cross-junction	0.0802	0.8712	0.0481	0.0006	− 33.48	2.49	64.94	132.08
Straight road	0.1356	0.8395	0.0247	0.0002	12.44	− 1.24	− 15.18	− 23.74
Road engineering								
Merging	0.1607	0.8201	0.0191	0.0001	33.28	− 3.52	− 34.52	− 49.90
Narrow	0.1367	0.8387	0.0244	0.0002	13.33	− 1.33	− 16.14	− 25.16
Sharp turn	0.0782	0.8718	0.0494	0.0006	− 35.13	2.56	69.55	143.30
Blind corner	0.1023	0.8612	0.0361	0.0003	− 15.16	1.32	23.90	42.89
Type of traffic								
Two-way	0.0847	0.8696	0.0453	0.0005	− 29.80	2.30	55.25	109.26
Dual carriageway	0.0790	0.8715	0.0489	0.0006	− 34.48	2.53	67.71	138.80
Expressway	0.0787	0.8716	0.0491	0.0006	− 34.75	2.54	68.48	140.68
Nature of lane								
Outermost	0.0940	0.8656	0.0401	0.0004	− 22.07	1.83	37.45	70.17
Outer	0.0963	0.8644	0.0389	0.0004	− 20.17	1.69	33.51	62.04
Center	0.0949	0.8651	0.0396	0.0004	− 21.34	1.78	35.93	67.00
Inner	0.1198	0.8505	0.0294	0.0002	− 0.64	0.06	0.88	1.46
Innermost	0.1112	0.8560	0.0325	0.0003	− 7.76	0.71	11.36	19.52
Surveillance camera	0.0837	0.8700	0.0459	0.0005	− 30.63	2.35	57.35	114.10
Wet road surface	0.1320	0.8421	0.0257	0.0002	9.48	− 0.93	− 11.86	− 18.77
Collision type								
Vehicles	0.0487	0.8712	0.0788	0.0013	− 59.60	2.49	170.23	450.98
Stationary object	0.0439	0.8684	0.0861	0.0016	− 63.56	2.16	195.46	547.18
Pedestrians	0.2137	0.7746	0.0116	0.0001	77.20	− 8.87	− 60.19	− 77.35
Nationality	0.1212	0.8496	0.0289	0.0002	0.51	− 0.05	− 0.69	− 1.13
Engine capacity max (1500 cc)	0.0613	0.8742	0.0637	0.0009	− 49.21	2.84	118.41	277.64

Table 5 (*continued*)

Name of the attributes	Estimated probability				Percent change relative to reference case (%)			
	No damage	Slight damage	Extensive damage	Total wreck	No damage	Slight damage	Extensive damage	Total wreck
Motorcyclist was offender	0.1170	0.8524	0.0304	0.0003	− 2.98	0.28	4.17	7.01
Headlight on during daytime	0.1324	0.8418	0.0256	0.0002	9.76	− 0.96	− 12.18	− 19.27
Age cohorts								
Less than 20	0.0749	0.8727	0.0518	0.0006	− 37.90	2.66	77.76	163.95
Age 20–29	0.0825	0.8704	0.0466	0.0005	− 31.62	2.40	59.93	120.15
Age 30–39	0.1006	0.8622	0.0369	0.0004	− 16.62	1.43	26.60	48.14
Age 40–49	0.1145	0.8540	0.0312	0.0003	− 5.03	0.46	7.16	12.14
Age 50–59	0.1331	0.8413	0.0254	0.0002	10.36	− 1.02	− 12.87	− 20.28
Age 60–69	0.1288	0.8444	0.0266	0.0002	6.81	− 0.66	− 8.71	− 13.98
Gender (male)	0.0866	0.8688	0.0441	0.0005	− 28.15	2.21	51.19	100.00
With pillion passenger	0.1293	0.8440	0.0265	0.0002	7.21	− 0.70	− 9.20	− 14.73

It is not apparent that the change in design standards (moving from lower to higher standards) matters with respect to changes in the probability of damage severity. Both the coefficient values and the relative changes in probability levels are all similar, although it is clear that the severity levels increase relative to one-way streets. Posted speed limits are somewhat correlated with the roadway types, for example, expressways have higher speed limits than dual carriageways, which may be an underlying factor for some of these effects. Posted speed limits are not included in the model due to their correlation with the road types.

The nature of the lane in which the accident occurred is estimated relative to a single lane. Interestingly, accidents on the outermost lanes appear to result in a greater probability of more severe injuries and more severe damage to the motorcycle, relative to those accidents on the inner lanes. These differences, while relatively small, may be the result of lane switching on the part of motorcyclists.

The presence of surveillance cameras are intended to be a deterrent to bad driving behavior and thus are expected to reduce accidents and presumably the relative severity of those accidents that do occur. Elvik, Vaa, and Østvik (1989) found that surveillance cameras resulted in a reduction in total injury accidents. While this study has no data on whether they reduce accidents, the results show a positive coefficient in both these models. This does not imply that the placement of surveillance cameras increases severity levels, but suggests that their placement may be endogenous and that they have been placed in locations with more severe accidents.

However, unlike the situation in many countries where surveillance cameras are installed at high-accident locations, in Singapore surveillance cameras (introduced some 15 years ago) were primarily developed to discourage red light running (Chin, 1989). Although an effective deterrent for red light runners, the surveillance camera may increase head-to-rear-end accidents on the approach as the motorcyclist may have difficulty in responding when forward vehicles stop suddenly (due to the presence of the camera).

Wet road surface conditions reduce the severity of both injuries and motorcycle damage. The probability of fatalities relative to dry road surfaces decreases by 20.6%. This is likely an effect of reduced speed levels under these conditions as motorcyclists compensate for the increased risk of driving when road surfaces are wet (Peltzman, 1975). This finding is consistent with other studies (e.g., Duncan et al., 1998; Shankar & Mannering, 1996).

The type of collision that occurs is estimated relative to single-vehicle accidents. Injury and damage severity is greatest when colliding with a stationary object. This type of accident has the greatest increase in the probability of a fatality of 480% (relative to accidents where no collision occurs). The severity of damage is also quite significant and the probability of a "total wreck" increases by 547%. Both injury severity and damage severity probabilities also increase significantly for collisions with other vehicles. One key difference between injury and damage severity coefficients is the positive coefficient value on injury severity for collisions with pedestrians (relative to single vehicle accidents) and the negative value in the damage severity model. There is a 77.3% reduced probability of a "total wreck" and a 328% increase in the probability of a fatality.

Significant differences were found in injury severity levels for those motorcyclists of different nationalities. A large number of commuters from Malaysia enter Singapore on motorcycles. Non-Singaporeans have more severe injuries but do not have any statistically significant difference in the severity of damage to the motorcycle. It is not clear why these differences occur, but it is possible that different licensing and training criteria may play a role. Singaporeans have about a 36.3% smaller probability of dying in accidents, relative to other nationalities.

The coefficient estimates show that injury and damage severities increase with increases in motorcycle engine capacity. Larger engine capacity motorcycles are larger in size, heavier in weight, and have greater power and potential speed. Langley et al. (2000) found that motorcycles with larger engine capacity appear to have an increased risk of crashing. His study suggested that cubic capacity is a poor measure of power and noted that an analysis of risk in terms of the power to weight ratio may provide a more useful insight into the benefits of motorcycle design restrictions for novice drivers. In the probability estimates derived here, a 1500 cc motorcycle, relative to the reference case of 170.29 cc, results in a 202% increase in the probability of a fatality and a 278% increase in the probability of a "total wreck."

When motorcyclists are classified as the offending driver, they tend to have a greater probability of more severe injuries and a small increase in the probability of a fatality. This does not seem to affect the likelihood of more severe damage to the motorcycle.

Those accidents where the motorcyclist had their headlight on during daytime tend to result in less severe injuries and less severe damage to the motorcycle. Having the headlights on during daytime may reflect more cautious behavior on the part of the motorcyclist, but could also allow other motorists to more readily take evasive action, thereby reducing the probability of more severe injuries and accident damage.

Dummy variables for motorcyclist age were included in both models and were estimated for drivers 70 years and older. While younger riders are usually expected to have an increased probability of being involved in an accident, it was found that their injury severity levels are not statistically different than for older riders. In fact, drivers in the 60–69 age group appear to have the highest injury severity levels, though only at an

85% level of confidence, relative to drivers even older. One would expect this age group to be more frail and thus more likely to have injuries, although the comparison group of those 70 and over would be expected to be more frail, so this interpretation is uncertain. In contrast, Mannering and Grodsky (1995) found that those aged between 26 and 39 are positively associated with medium-risk categories of injury. Women were found to have a higher probability of a more severe injury relative to men, which is consistent with the findings of Evans (1991), Kim, Nitz, Richardson, and Li (1995) and O'Donnell and Connor (1996). This is likely due to physiological differences. However, the results derived here show that the probability levels for a fatality for male and female drivers differs by only 1%, thus this hypothesis is not supported by the analyses.

Motorcyclist age, however, does appear to be a factor in increased motorcycle damage severity. Those less than 20 and those in the 20–29 age group have more severe motorcycle damage, relative to other age groups. Men also have a greater likelihood of increased motorcycle damage, with a 100% increase in the probability of a "total wreck" relative to women drivers. This clearly suggests that these age groups and male motorcyclists engage in riskier driving behavior.

In Singapore, many motorcyclists have a pillion passenger. When a pillion passenger is present, the injury severity increases, but the damage severity is less. This may partially be an artifact of having at least two people involved in the accident, which would increase the chances of the accident being classified with a higher severity ranking.

5. Conclusions

In this study, an ordered probit model was used to investigate how variations in various factors, including specific characteristics of the roadway and the rider, can lead to variations in the level of both injury severity and of damage severity to the motorcycle. A large and highly disaggregated data set from Singapore was used to estimate the model parameters. The ordered probit model allowed the evaluation of the statistical significance of various factors as well as the changes in the relative probability of the severity levels.

It was found that both motorcycle injury severity and damage severity are decreasing over time, which implies that other unmeasured factors are having a beneficial effect on these measures. Time-of-day effects were also found to be important, particularly in the early morning hours. Various road engineering and design features were also examined. Of most interest, it was found that higher road design standards increase the probability of severe injuries and fatalities for motorcycle-involved accidents. This result does not support the hypothesis that higher design standards lead to safer roads, although the probability of an accident occurring as a function of the design standards is not examined. One likely factor for this effect is that excessive speed may play a part in these types of accidents, although these data do not allow a detailed investigation of speed effects.

The main factors that result in more severe injuries appear to be collisions with stationary objects, collisions with pedestrians, and the engine capacity of the motorcycle. Similar factors result in increased damage to the motorcycle, although collisions with pedestrians seem to result in less damage.

There was no evidence to support the hypothesis that increased age systematically increases the level of injury severity and no evidence of a substantive difference between men and women.

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