Pergamon

Journal of Safety Research, Vol. 27, No. 3, pp. 183–194, 1996
Copyright © 1996 National Safety Council and Elsevier Science Ltd
Printed in the USA. All rights reserved
0022-4375/96 $15.00 + .00

PII S0022-4375(96)00010-2

An Exploratory Multinomial Logit Analysis of Single-Vehicle Motorcycle Accident Severity

Venkataraman Shankar and Fred Mannering

Most previous research on motorcycle accident severity has focused on univariate relationships between severity and an explanatory variable of interest (e.g., helmet use). The potential ambiguity and bias that univariate analyses create in identifying the causality of severity has generated the need for multivariate analyses in which the effects of all factors that influence accident severity are considered. This paper attempts to address this need by presenting a multinomial logit formulation of motorcycle-rider accident severity in single-vehicle collisions. Five levels of severity are considered: (a) property damage only, (b) possible injury, (c) evident injury, (d) disabling injury, and (e) fatality. Using 5-year statewide data on single-vehicle motorcycle accidents from the state of Washington, we estimate a multivariate model of motorcycle-rider severity that considers environmental factors, roadway conditions, vehicle characteristics, and rider attributes. Our findings show that the multinomial logit formulation that we use is a promising approach to evaluate the determinants of motorcycle accident severity.

INTRODUCTION

Motorcycles provide an efficient form of transportation with respect to environmental, spatial, and nonrenewable (e.g., fossil fuels) resource concerns. However, despite advantages in these areas relative to passenger cars, motorcycles have declined in popularity since their peak years in the late 1960s. To some extent, this decline can be explained by the comparatively high accident risk and high risk of severe injury associated with motorcycle riding. To this end, statistical analyses of the likelihood of motorcycle accidents and their severity have the potential to uncover underlying causality and clarify possible misunderstandings relating to motorcycle safety. Such analyses could help identify factors that one can control to keep motorcycle risks at an acceptable level, thereby saving lives, preventing injuries, and making motorcycling a more competitive mode of travel.

Venkataraman Shankar is currently a PhD candidate in the Civil Engineering Department at the University of Washington. He received his Masters degree from the University of Washington in 1990. He has authored a number of papers on vehicular safety and the focus of his dissertation is the application of new methodological approaches to vehicle-safety research.

Fred Mannering is a professor in the Civil Engineering Department at the University of Washington. He received his PhD from the Massachusetts Institute of Technology in 1983. Dr. Mannering has authored numerous papers in the areas of travel demand, economics, vehicular safety, automobile demand, statistical methodologies, and transportation network analysis.

Recent studies have shown that motorcyclists are generally aware of the key factors that contribute to an increased risk of an accident. For example, Mannering and Grodsky (1994) found that factors such as driving exposure, riding at speeds that exceed posted speed limits, improper lane changes, and passing on double yellow lines, were all recognized by motorcyclists to increase the likelihood of an accident. However, accident severity (as opposed to the likelihood of an accident occurring) presents another, arguably less understood, phenomenon. The study of the determinants of the conditional distribution of accident severity (i.e., conditioned on the occurrence of an accident) has the potential to provide additional insights into the true consequences of motorcyclists' behavior (e.g., speeding, helmet use, etc.) and the interactions of this behavior with environmental, roadway, and vehicle characteristics.

Most previous research on motorcycle accident severity has focused on issues relating to head injuries and fatalities (see Chenier & Evans, 1987; Gabella, Reiner, Hoffman, Cook, & Stallones, 1995) and on helmet-related issues such as patterns of head injuries and effectiveness of helmets in reducing both fatalities and severity of head injuries (Bachulis, Sangster, Gorrell, & Long, 1988; Evans & Frick, 1986; Foldvary & Lane, 1964; Watson, Zador, & Wilks, 1980). Unfortunately, most previous research has been oriented toward a univariate examination of accident severity (with respect to issues such as helmet use or alcohol consumption). Comparatively little research has been conducted in the area of motorcycle safety using a true multivariate examination of the determinants of accident severity (i.e., controlling for all factors influencing accident severity). If one does not use a multivariate approach, it is possible that a systematic bias could result as well as ambiguity in the interpretation of causality. Research by Goldstein (1986) and Weiss (1992) has made important contributions by modeling the simultaneous effects of several variables (i.e., a true multivariate approach) on motorcycle accident severity. Goldstein employed a tobit model to investigate head, neck, and body injuries and Weiss employed the ordered probit model to examine the severity of head injuries based on the Hurt data (Hurt, Ouellet, & Thom, 1981). These studies have provided an important first step in the multivariate analysis of motorcycle accident severity.

In contrast, multivariate studies of automobile accident severity have been more common, and such studies have the potential to provide some general insight into the factors that determine motorcycle accident severity. Examples of automobile-severity studies include the work of Jones and Whitfield (1988) in which logistic regression was used to model the severity risk as a function of anthropometric measures, vehicle mass, age of rider, and restraint system use. Logistic regression was also employed by Lui, McGee, Rhodes, and Pollock (1988) to model the probability of fatalities conditioned on the occurrence of an accident using variables such as driver age, gender, impact points, vehicle crash severity, restraint system use, and vehicle mass. Other methodologies such as multivariate time-series (Lassarre, 1986), double-pair comparison (Evans, 1986), headway-based severity (Glimm & Fenton, 1980), bivariate probit (Hutchinson, 1986), and discriminant analysis (Shao, 1987) have been successfully applied. Finally, Shankar, Mannering, and Barfield (in press) have shown the potential of the nested logit specification by using environmental, geometric, weather, vehicular, and human factors to develop a predictive model of automobile accident severity.

The present study attempts to extend the empirical and methodological contributions of previous work (drawing on past findings from studies of both automobile and motorcycle accident severity) by developing a model of motorcycle-rider accident severity (for single-vehicle accidents) that can be used to understand the impacts of helmet use, alcohol-impaired riding, and other factors, on accident severity. The focus on single-vehicle accidents allows us to concentrate on accidents in which the motorcyclist was likely to have made an error in judgment, and thus we avoid the variability in accident severity introduced when multiple-vehicles are involved (i.e., cases where automobiles may significantly influence the overall accident severity).

Our paper begins with a discussion of the proposed methodological approach. This is followed by a description of data used in model estimation. We then present model estimation results and a detailed discussion of our findings and their implications for accident severity analysis. The paper concludes with a brief discussion of model specification issues, a summary, and directions for future research.

METHODOLOGY

We begin by developing a conditional model of motorcycle accident severity, that is a model conditioned on the fact that a single-vehicle motorcycle accident has occurred (see Shankar, Mannering, & Barfield, 1995, for a study of the likelihood of an accident occurring). Severity of a single-vehicle motorcycle accident is specified to be one of five discrete categories: (a) property damage only, (b) possible injury, (c) evident injury, (d) disabling injury, and (e) fatality. The injury classification is made on the basis of rider injuries only, the injuries to passengers (if any) are not considered (this will be discussed again later in the paper). Given these five discrete severity categories, a statistical model that can be used to determine the probability of an accident having a specific severity level can be derived. We start the derivation with the following probability statement,

$$P_n(i) = P(S_{in} \geq S_{In}) \ \forall \ I \neq i \qquad (1)$$

where $P_n(i)$ is the probability that accident n is severity i, P denotes probability and S_{in} is a function of covariates that determine the likelihood of accident n being severity i (I is the set of possible severities). To estimate this probability, a function defining the severity likelihoods must be specified. We use a linear form such that,

$$S_{in} = \beta_i X_n + \varepsilon_{in} \qquad (2)$$

where $\mathbf{X}_n$ is a vector of measurable characteristics that determine the severity (e.g., rider age, rider gender, roadway attributes, prevailing weather conditions, vehicle type, use of helmets, and so on), β_i is a vector of estimable coefficients, and ε_{in} is an error term that accounts for unobserved factors influencing accident severity. The term $\beta_i \mathbf{X}_n$ in this equation is the observable component of severity determination because the vector $\mathbf{X}_n$ contains measurable variables (e.g., roadway attributes at the location of accident n), and in is the unobserved portion.

Given equations 1 and 2, the following can be written,

$$P_n(i) = P(\beta_i X_n + \varepsilon_{in} \geq \beta_I X_n + \varepsilon_{In}) \ \forall \ I \neq i \qquad (3)$$

or,

$$P_n(i) = P(\beta_i X_n - \beta_I X_n \geq \varepsilon_{In} - \varepsilon_{in}) \ \forall \ I \neq i \qquad (4)$$

With equation 4, an estimable severity model can be derived by assuming a distributional form for the error term. A natural choice would be to assume that this error term is normally distributed. Such an assumption results in a probit model. However, probit models are computationally difficult to estimate (see Ben-Akiva & Lerman, 1985). A more common approach for models of this type is to assume that ε_{in}'s are generalized extreme value (GEV) distributed. The GEV assumption produces a closed form model that can be readily estimated using standard maximum likelihood methods. It can be shown (McFadden, 1981) that the GEV assumption produces the simple multinomial logit model,

$$P_n(i) = \exp[\beta_i X_n] \Big/ \sum_I \exp[\beta_I X_n] \qquad (5)$$

where all variables are as previously defined and the vector β_i is estimable by standard maximum likelihood methods.

EMPIRICAL SETTING

Data on single-vehicle motorcycle accidents (i.e., accidents involving one motorcycle) were obtained from the Washington State Department of Transportation accident files. These files contain data that can be classified into five categories: (a) general accident data, (b) weather data, (c) pavement surface data, (d) vehicle data, and (e) rider-related data. General accident data included information on rider injury in terms of the five accident-severity categories (i.e., property damage only, possible injury, evident injury, disabling injury, and fatality, as previously discussed); rider injury classifications (such as head, torso, limb, or multiple injuries); time of day of accident; accident location with respect to the traveled way (on or off the roadway, whether the accident occurred on a curve or straight section or a grade, roadway illumination information, types of roadside objects involved in collision, and accident type); and roadway functional classification. Weather data contained information on atmospheric conditions at the time of the accident (e.g., rain, snow, fog) and pavement-related data contained information on pavement surface conditions at the time of the accident (e.g., ice, snow, wet, or dry). Vehicle data included information on motorcyclists' helmet use, ejection status of occupants (i.e., whether or not the motorcyclist was ejected from the vehicle), motorcycle headlight operating condition at the time of accident (whether headlights were on), and whether or not a passenger was present. Motorcycle rider-related data included information on sobriety at the time of accident, age, gender, and rider action leading to the accident (e.g., inattention, not granting right of way, improper passing, excessive speed, and so on).

Our accident data was drawn from a 5-year period between 1989 and 1994. Over this period, there were a total of 3,469 reported accidents involving a motorcycle, 1,594 (45.95%) of which were single-vehicle accidents (there were 1,715 two-vehicle accidents and 160 accidents involving 3 or more vehicles). Before proceeding, it is important to discuss the consequences of using only reported accidents as a basis for estimating our severity model and the consequences of using police officer judgments of severity instead of actual medical records. The concern with using only reported accidents is that it is likely that many accidents (particularly those that are minor in severity) may go unreported. This means that our accident sample is not a random sample of all accidents. Fortunately this under-reporting will have a minimal impact on multinomial logit model estimation results. In fact, all coefficients will be correctly estimated with the exception of the constant terms. If the number and severity of unreported accidents were known, the constant term reported in this paper could be adjusted by a simple calculation and no additional estimation would be necessary (see Ben-Akiva & Lerman, 1985, for details on such stratified-sample adjustments).

With regard to our using police officer judgments of severity as opposed to actual medical records, some caution should be exercised in interpreting our findings. This is because several studies have shown discrepancies between officer judgments and medical records. For example, Barancik and Fife (1985) found that 15% of patients showing up at emergency departments for vehicle-related injuries had police reports that indicated no injury. Barancik and Fife go on to note that officer reports are much more likely to be accurate when estimating the severity of the injury to the vehicle driver relative to passengers. It could be argued that the extent of severity misjudgment, in our case, is less likely to be a serious problem because we consider only the injuries of the motorcycle operator and not passengers. However, our findings should be viewed with this potential bias in mind.

Of the 1,594 single-vehicle motorcycle accidents, 944 had missing data and thus the sample was reduced to 650. An analysis of this reduced sample, by statistically comparing the means of variables contained in both the reduced sample and the entire sample, revealed no systematic bias resulting from the elimination of observations with missing data. This suggests that missing data seems to be random (i.e., perhaps due to random data recording mistakes and omissions) and not correlated with the severity or other accident-related attributes. Of the 650 accidents included in our sample, 32 resulted in property damage only, 86 resulted in possible injuries, 176 resulted in evident injuries, 322 resulted in disabling injuries, and 34 resulted in fatalities. As stated previously, the injury classification is made using rider injuries only — injuries to passengers (if any) are not considered (only 18.31% of the 650 accident-involved motorcycles had a passenger at the time of the accident). It should also be noted here that possible injury accidents (which may seem to be a somewhat vague category) are determined at the scene by Washington State troopers using well-defined, uniformly taught identification procedures. Our testing of various model structures suggests that this is a unique severity category and must be considered separately (i.e., even though the accident will eventually be classified as an injury or a property damage only accident).

Table 1 provides information on the distribution of accident severity by important conditioning variables such as helmet use, sobriety, functional classification of roadway, engine displacement, and whether or not the accident occurred at an intersection. An interesting point in this table is the comparatively high number of riders that were nonhelmeted at the time of the accident (12.15%). Although Washington State had a helmet law in effect throughout this period, it was declared unconstitutional for much of 1993 (during which time many law-enforcement agencies refused to enforce it) until it was rewritten. Thus it appears that quite a few riders reverted to nonhelmet use during this period. As will be shown in forth-

TABLE 1
SINGLE-VEHICLE MOTORCYCLE ACCIDENT SEVERITY DISTRIBUTION BY KEY VARIABLES

Accident Conditioning Variable	Percent of Entire Sample	Severity Frequency				
		Property Damage	Possible Injury	Evident Injury	Disabling Injury	Fatality
Helmet use	87.85	28	80	149	285	29
Helmet not used	12.15	4	6	27	37	5
Alcohol-impaired riding	21.08	1	13	52	55	16
Sober riding	78.92	31	73	124	267	18
Interstate location	29.85	9	37	40	100	8
Arterial location	53.08	15	43	100	167	20
High displacement (greater than 500cc)	60.92	17	49	113	193	24
Intersection location	17.38	4	18	23	67	1
Non-intersection location	82.62	28	68	153	255	33

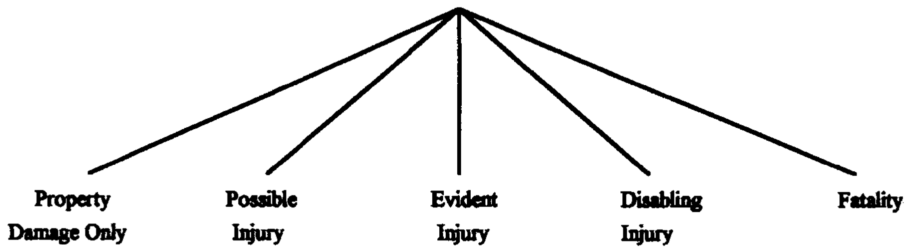
coming model estimation, having 12.15% of the sample being nonhelmeted is a large enough percentage to produce highly significant findings with regard to the impact of helmets on accident severity (as measured by *t*-statistics). Finally, Table 2 shows the frequency and percentage of accidents conditioned on several of these variables.

TABLE 2
ACCIDENT FREQUENCY AND PERCENTAGE BY CONDITIONING VARIABLE

Primary Accident Conditioning Variable	Interaction Variable	Frequency	Percentage
Helmet	Fixed-object Collision	201	35.20
	Non-fixed-object Collision	370	64.80
No helmet	Fixed-object Collision	34	43.03
	Non-fixed-object Collision	45	56.97
Wet pavement	Dry Weather	28	49.1
	Rainy Weather	29	50.9
Exceeding speed limit	None	59	9.08
No helmet	Low-speed Riding (less than 72 km/h)	28	35.44
	High-speed Riding (72 km/h or higher)	51	64.56
Alcohol-impaired riding	Helmeted	107	78.10
	Non-helmeted	30	21.90
Inattention	None	80	12.31
Interstate location	None	194	29.85
Rider ejected	None	464	71.38
High-displacement (greater than 500 cc)	None	396	60.92
Young rider (less than 21 years old)	High Displacement (greater than 500 cc)	64	68.09
	Low Displacement (500 cc or less)	30	31.91

Note: Percentages for the exceeding speed limit, inattention, interstate, rider ejected and high-displacement variables are given in relation to the entire sample. Percentages for other variables shown are shown by primary class, i.e. helmet, no-helmet, alcohol-impaired riding, and young rider.

FIGURE 1
ACCIDENT SEVERITY MODEL STRUCTURE



MODEL ESTIMATION

Estimation of the multinomial logit specification (with severity alternatives as shown in Figure 1) was carried out using standard maximum likelihood methods. Results of the estimation are shown in Table 3. This table shows that the signs of all model coefficients are of plausible sign and that the model has good overall convergence, with the log-likelihood converging from –1046.1 to –779.22, giving a ρ^2 of 0.256. An interpretation of the model findings is provided below.

Variable: Helmeted-rider/fixed object interaction.
Finding: Increases the likelihood of fatality.

It is generally believed that helmet use tends to decrease the occurrence and severity of head injuries. It is also widely believed that helmets, by themselves, will be most effective in reducing fatalities where head injuries are the primary cause of death. However, the effectiveness of helmet use in reducing fatalities when other factors (e.g., speed, roadway conditions) are considered, is not well understood. Our finding that helmeted riders have an increased likelihood of being fatally injured when colliding with fixed objects, while seeming improbable at first glance, could be explained in at least three ways. First, the increased likelihood of a fatal injury could be due to some physiological factors associated with helmeted riders hitting fixed objects in single-vehicle collisions. Second, the increased likelihood could be an outgrowth of helmeted riders tending to ride more recklessly in response to that added sense of security that a helmet provides (i.e., risk compensation as previously explored by researchers such as Peltzman, 1975, and Adams, 1983). Third, riders choosing not to wear a helmet could be a self-selected group that has riding habits and skills that make them less susceptible to fatal injuries in fixed-object accidents. Unfortunately, our sample of nonhelmeted fatalities in fixed-object collisions is too small to statistically explore this third possibility in detail. It must be pointed out that, although our finding relating to this interaction term is highly significant (t-statistic = 4.57), further research into this somewhat surprising finding is warranted with a larger data set that includes a greater number of nonhelmeted riders.

Variable: No-helmet/fixed-object interaction.
Finding: Increases the likelihood of evident injury.

This variable indicates that nonhelmeted riders face a greater risk of evident injury, relative to other types of accident severities, when they are involved in fixed object collisions. It is possible that nonhelmeted riders may be cognizant of the risks of riding without a helmet and maintain lower speeds, and/or they could be a self-selected sample of more experienced, safer riders. These possibilities could explain their increased likelihood of evident injury as opposed to the more serious severity categories of disabling injury and fatality.

Variable: No-helmet/alcohol-impaired riding interaction.
Finding: Increases the likelihood of fatality.

This variable captures both the lack-of-awareness and risk-taking behavior of alcohol-impaired riders (those riders with their abilities impaired by alcohol, as determined by the officer at the accident scene). Several studies (Murdock & Waxman, 1991; Nelson, Sklar, Skipper, & McFeeley, 1992) have found a strong association between alcohol use and nonhelmeted riding. Although this could

TABLE 3
ESTIMATION OF THE MULTINOMIAL LOGIT MODEL OF MOTORCYCLE-RIDER SEVERITY

Variable	Estimated Coefficient	t-statistic
Constant (specific to fatality)	-3.13	-8.06
Helmeted-rider-fixed object interaction indicator (1 if rider was helmeted and hit a fixed object, 0 otherwise; specific to fatality)	2.02	4.57
No-helmet, fixed object interaction indicator (1 if rider was non-helmeted and hit a fixed object, 0 otherwise; specific to evident injury)	0.81	2.18
No-helmet, alcohol-impaired riding interaction indicator (1 if rider was non-helmeted and alcohol impaired, 0 otherwise; specific to fatality)	2.36	3.49
No-helmet, low-speed riding interaction indicator (1 if rider was non-helmeted and estimated speed at time of accident was less than 72 km/h, 0 otherwise; specific to evident and disabling injury)	1.41	1.84
Alcohol-impaired riding indicator (1 if riding ability was impaired by alcohol, 0 otherwise; specific to fatality, evident injury and disabling injury)	0.78	2.49
Motorcycle displacement indicator (1 if displacement is greater than 500 cc, 0 otherwise; specific to fatality, evident injury and disabling injury)	0.31	1.49
Age-displacement interaction indicator (1 if rider age is less than 21 years old and displacement of motorcycle is greater than 500 cc, 0 otherwise; specific to property damage, disabling injury and possible injury)	0.77	2.46
Motorcycle rider age as a continuous variable (specific to fatality and disabling injury)	0.014	4.57
Ejection of rider indicator (1 if rider was ejected, 0 otherwise; specific to fatality, evident injury, disabling injury and possible injury)	1.05	3.17
Speeding indicator (1 if exceeding speed limit was the primary cause of the accident, 0 otherwise; specific to fatality, evident injury and disabling injury)	0.88	1.95
Vehicle speed at the time of accident as a continuous variable (specific to fatality, evident injury and disabling injury)	0.014	3.24
Rider inattention indicator (1 if inattention was the primary cause of the accident, 0 otherwise; specific to evident and disabling injury)	0.85	2.36
Roadway type indicator 1 (1 if accident occurred on an interstate freeway, 0 otherwise; specific to disabling injury)	0.41	2.22
Roadway type indicator 2 (1 if accident occurred on an interstate freeway, 0 otherwise; specific to possible injury)	0.87	3.22
Wet pavement/not-raining interaction indicator (1 if pavement surface was wet and it was not raining at the time of accident, 0 otherwise; specific to property damage and possible injury)	1.56	3.77
Number of observations		650
Log-likelihood at zero		-1046.1
Log-likelihood at convergence		-779.22
ρ^2		0.256

be true in a general context, the finding on alcohol-impaired riding without a helmet suggests that riding without a helmet while alcohol-impaired is indeed a deadly combination.

Variable: No-helmet/low-speed interaction.
Finding: Increases the likelihood of evident and disabling injury.

This finding has important ramifications in unraveling the true effectiveness of helmets when speed is taken into account. Intuitively one might expect that riding without a helmet would predispose riders to a greater risk of fatality. However, our finding here suggests that when the interaction with speed is taken into account, this expectation is tempered by the presence of several mitigating factors such as low speed riding, less-risky riding behavior, and the possibility that nonhelmeted riders may be a self-selected group of safer riders. While riders traveling at speeds less than 72 km/h without a helmet are less likely to be involved in an accident in which they are fatally injured, our results show that they are also less likely to be involved in property damage only and possible injury accidents. Thus such behavior increases the likelihood that the accident will be in the middle of the severity range.

Variable: Alcohol-impaired riding.
Finding: Increases the likelihood of fatality, evident, and disabling injuries.

This finding is consistent with several studies (Luna, Maier, Sowder, Copass, & Oreskovich, 1984; Waller et al., 1985) that have reported that alcohol has a strong association with an increase in traumatic injury in vehicular accidents. This variable captures inherent risk-taking tendencies in alcohol-impaired riders and also the potential of alcohol to increase the severity of head injuries once a crash has occurred (see Waller et al.).

Variable: Motorcycle displacement.
Finding: Increases the likelihood of fatality, evident, or disabling injuries.

This variable, used as an indicator for displacements exceeding 500 cc, suggests that higher displacement vehicles pose a greater risk of severe forms of injury to riders, perhaps as a result of the effects that such vehicles may have on rider behavior and/or the higher vehicle weight associated with larger displacement motorcycles.

Variable: Age-displacement interaction.
Finding: Increases the likelihood of property damage, possible injury, and disabling injury.

This variable captures an interesting causal process behind the interaction of age and displacement. Young riders (aged 20 or less) when riding motorcycles of displacement 500 cc or higher are either prone to be involved in collisions of mild severity such as property damage and possible injury or severe injury such as disabling injuries. While this variable by itself would appear to predispose young riders to severe forms of injury including fatalities, when aggravating factors such as speed and alcohol-impaired riding are controlled for, the risk of evident injury seems to be reduced to milder forms while the risk of fatality seems to be reduced to disabling injuries.

Variable: Motorcycle rider age.
Finding: Increases the likelihood of fatality and disabling injury.

This variable captures the simultaneous effect of several factors. Although older riders may tend to ride at lower speeds and be less likely to be in an accident, once in an accident they tend to have severe injuries. This may be due to physiological factors associated with advanced age.

Variable: Ejection of rider.
Finding: Increases the likelihood of any form of injury relative to property damage.

From a statistical perspective, this variable may be endogenous because riders with more severe injuries (i.e., injuries incurred as the accident evolves) may be more likely to be ejected. This means that a left-side (dependent) variable, injury severity, can change the value of the right-side variable, rider ejection. If the model were to be estimated without considering this possible endogeneity, model coefficient estimates would be biased and inconsistent. To resolve this potential specification problem, we estimate a binary logit model of ejection probability (using all other exogenous variables as predictors) and use the estimated probability of being ejected from this model as the variable in our severity model. This approach ensures unbiased and consistent model estimation.

The resulting coefficient estimate confirms earlier expectations — that ejection from the motorcycle tends to result in some form of injury primarily due to the impact with some hard object or the pavement, at speed.

Variable: Speeding.
Finding: Increases the likelihood of fatality, evident injury, and disabling injury.

This finding indicates that if the collision occurs due to the rider exceeding the speed limit, the consequence is likely to be some severe form of injury. This underscores the dangers of riding at speeds that exceed the design limits of the highway.

Variable: Vehicle speed at time of accident.
Finding: Increases the likelihood of fatality, evident injury, and disabling injury.

This finding shows, as expected, that the likelihood of injury increases to more severe forms as vehicle speed increases. This variable captures the gradual increase in urgency and complexity of the riding task as riding speed increases, and the increase in kinetic energy that must be dissipated (often on the body) as speed increases.

Variable: Rider inattention.
Finding: Increases the likelihood of evident and disabling injury.

When rider inattention is identified as the primary factor for accident occurrence, it indicates that speed was a less significant factor. As a result, the rider tends to be less prone to fatal injury but is more prone to evident or disabling injuries as a result of improper evasive action.

Variable: Interstate as a roadway type.
Finding: Increases the likelihood of disabling and possible injury.

This variable indicates that, given that the accident occurred on an interstate freeway, its severity is more likely to be in the possible and disabling injury categories. Interstates, although high-speed facilities, are the safest class of roadways in the United States, with adequate radii on curves, ample sight distance on grades, and limited access by design. In addition, interstate riders seem to have higher helmet use (perhaps due to riders' increased perception of danger due to higher speeds and more stringent helmet law enforcement), with less than 5% of interstate accidents involving nonhelmeted riders as opposed to more than 12% in the overall sample. The combination of these factors seems to concentrate single-vehicle motorcycle accident severity probabilities toward possible and disabling injuries and away from property damage only, evident injury, and fatality.

Variable: Wet pavement/not-raining interaction.
Finding: Increases the likelihood of property damage and possible injury.

This variable suggests that if the accident occurred on wet pavement with no rain falling, the severity of the crash tends to be limited to property damage and possible injury. Wet pavements may be acting as visual deterrents to speeding, which may encourage motorcyclists to maintain longer headways and lower riding speeds.

To examine the marginal effects of some key factors, elasticities of the variables included in the model were estimated. The elasticity of variables, in our case, will measure the responsiveness of the probability of some accident-severity category to changes in variable values. In general, elasticity is computed as

$$E_{x_n}^{P_n(i)} = \frac{\partial P_n(i)}{\partial x_n} \bullet \frac{x_n}{P_n(i)} \tag{6}$$

were E represents the elasticity, x is the value of the variable being considered, and $P_n(i)$ is the probability of accident n being of severity i. Applying this equation to the multinomial logit formulation (equation 5) gives

$$E_{x_n}^{P_n(i)} = \left(1 - \sum_{J} P_n(j)\right) \beta_i x_n \tag{7}$$

where J is the set of alternatives that have the variable x_n in their severity function (S_{in} in equation 2). Equation 7 is only valid for continuous variables (x) such as rider age and vehicle speed. For noncontinuous variables (i.e., those variables that take on values of zero or one, such as riding when alcohol-impaired or riding a motorcycle over 500 cc in displacement) we estimate a "pseudo-elasticity" that captures the approximate elasticity of the variable. In the multinomial logit formulation this pseudo elasticity is given as

$$E_{x_n}^{P_n(i)} = \frac{\exp[\Delta(\beta_i X_n)]\sum_{J}\exp[\beta_j X_n]}{\exp[\Delta(\beta_i X_n)]\sum_{J}\exp[\beta_j X_n] + \sum_{J\neq i}\exp[\beta_j X_n]} - 1 \tag{8}$$

where all variables are as previously defined.

Table 4 presents the elasticity computations for some select variables. As an intuitive example of what these values mean, the elasticity of rider age (the value of which is 0.198 from Table 4) means that a 1% increase in a rider's age results in a 0.198% increase in the probability

TABLE 4
ELASTICITIES OF KEY DETERMINANTS OF MOTORCYCLE-RIDER ACCIDENT SEVERITY

Variable (see corresponding variable definitions in Table 3)	Elasticity/Pseudo-Elasticity
Helmeted-rider-fixed object interaction (specific to fatality)	5.669
No-helmet, fixed object interaction (specific to evident injury)	0.694
No-helmet, alcohol-impaired riding interaction (specific to fatality)	6.949
No-helmet, low speed riding interaction (specific to evident and disabling injury)	0.235
Alcohol-impaired riding (specific to fatality, evident injury and disabling injury)	0.483
Motorcycle displacement (specific to fatality, evident injury and disabling injury)	0.223
Age-displacement interaction (specific to property damage, disabling injury and possible injury)	0.322
Motorcycle rider age (specific to fatality and disabling injury)	0.198
Ejection of rider (specific to fatality, evident injury, and disabling injury and possible injury)	0.714
Speeding (at time of accident, specific to fatality, evident injury and disabling injury)	0.531
Vehicle speed at the time of accident (specific to fatality, evident injury and disabling injury . . .	0.112
Rider inattention (inattention at time of accident, specific to evident and disabling injury)	0.172
Roadway type indicator 1(interstate freeway accident, specific to disabling injury)	0.216
Roadway type indicator 2 (interstate freeway accident, specific to possible injury)	1.082
Wet pavement/not-raining interaction (specific to property damage and possible injury)	2.021

that the rider's accident will be either a disabling injury or fatality. Other values in this table can be interpreted in a similar manner. The results in Table 4 show that only helmeted-fixed object, alcohol-impaired riding while without a helmet, and pavement surface/weather interactions as well as the interstate freeway indicator (with possible injury) were found to be elastic (i.e., an elasticity value greater than 1). This underscores the comparative importance of these four variables in estimating single-vehicle motorcycle accident severity.

MODEL SPECIFICATION ISSUES

The multinomial logit model used in this paper (as shown in equation 5) can potentially be afflicted with a serious specification problem because the derivation of this model requires us to assume that the unobserved terms (ε_{in}'s) are independent from one severity type to another. Intuitively, it is possible that some severity types could share unobserved terms and have a correlation that violates the assumption made during model derivation. For example, property damage only and possible injury accidents may share unobservables such as internal injury or effects associated with lower-severity accidents. In the presence of shared unobservables, the logit formulation will erroneously estimate the model coefficients. The problem of shared unobservables is referred to as an independence of irrelevant alternatives (IIA) specification error. To test for the possibility of this error, the Small-Hsiao test of the IIA assumption was used (Small & Hsiao, 1985). The test results showed that IIA violations were not significant in our model at the 95% confidence level. We thus conclude that our model is properly specified with regard to this important IIA concern (see Shankar et al., in press, for an alternative model formulation when the IIA property is violated).

SUMMARY AND DIRECTIONS FOR FURTHER RESEARCH

This paper provides an important methodological framework (i.e., the use of a multinomial logit specification) for estimating motorcycle rider accident severity likelihood conditioned on the occurrence of an accident. In association with the extant body of research on motorcycle safety, the findings of this study confirm some previous conclusions, and more importantly unravel some causal processes underlying single-vehicle motorcycle accident severity. By developing a probabilistic model that contains several important variables relating to environmental factors, roadway conditions, vehicle characteristics, and rider attributes, we have shown that possible ambiguity and bias stemming from confounding effects in a partially specified model (i.e., a model that does not include all relevant variables, which produces an omitted variables specification error) can be eliminated. In addition, this research provides suggestive results by its use of variables such as helmet-sobriety interaction and helmet-fixed object interaction. Specifically, it suggests that helmeted-riding may be an effective means of reducing injury severity in some types of collisions, however, the benefit of helmet use may be offset in fixed-object collisions where the risk of fatality was found to increase. This increase could be due to the possibility that riders not wearing a helmet represent a self-selected sample with riding behavior/experience that makes them less prone to fatal injuries, could be the outgrowth of some physiological factors associated with helmeted riders hitting fixed objects in single-vehicle collisions, or could be the result of some form of risk compensation among helmeted riders. In general, our findings with regard to helmet use and accident severity suggest a rather complex interaction and one that could benefit from an analysis similar to that conducted in this paper, but on a more extensive, and perhaps national, database.

Our analysis also uncovered many important relationships between accident severity and motorcycle displacement, rider age, alcohol-impaired riding, rider ejection, speed, rider attention, pavement surface, and type of highway. The wide diversity of variables found to influence accident severity suggests a number of important directions for future motorcycle accident severity research. First, a study that considers multivehicle accidents should be undertaken. Such a study would require a large data set because of the additional variability introduced by the many different vehicle types that could influence severity, but additional, important conclusions could be drawn. Second, the methodological approach demonstrated in this paper needs to be applied to larger and more detailed databases. In the past, studies that have used large and detailed motorcycle-accident databases have tended to apply comparatively simplistic statistical approaches that have greatly limited the usefulness of their findings. Finally, it would be interesting to conduct the severity analysis proposed in this paper using actual medical records as compared to the police officer judgments used herein. The use of such records would permit a quantification of any potential biases that may result from using police officer judgments that are commonly available in national accident databases.

REFERENCES

Adams, J. G. (1983). Public safety legislation and the risk compensation hypothesis: The example of motorcycle helmet legislation. *Environment and Planning C: Government and Policy, 1*, 193–203.

Bachulis, B. L., Sangster, W., Gorrell, G. W., & Long, W. B. (1988). Patterns of injury in helmeted and nonhelmeted motorcycles. *American Journal of Surgery, 155*, 708–711.

Barancik, J. I., & Fife, D. (1985). Discrepancies in vehicular crash injury reporting: Northeastern Ohio trauma study IV. *Accident Analysis and Prevention, 17*(2), 147–154.

Ben-Akiva, M., & Lerman S. R. (1985). *Discrete choice analysis: Theory and application to travel demand.* Cambridge, MA: The MIT Press.

Chenier, T. C., & Evans, L. (1987). Motorcyclist fatalities and the repeal of mandatory helmet wearing laws. *Accident Analysis and Prevention, 18*, 133–139.

Evans, L. (1986). Double pair comparison a new method to determine how occupant characteristics affect fatality risk in traffic crashes. *Accident Analysis and Prevention, 18*(3), 217–228.

Evans, L., & Frick, M. C. (1986). *Helmet effectiveness in preventing motorcycle driver and passenger fatalities* (Research Publication GMR-5602). Warren, MI: General Motors Research Laboratories.

Foldvary, L. A., & Lane, J. C. (1964). The effect of compulsory safety helmets on motorcycle accident fatalities. *Australian Road Research, 2*, 7–24.

Gabella, G., Reiner, K. L., Hoffman, R. E., Cook, M., & Stallones, L. (1995). Relationship of helmet use and head injuries among motorcycle crash victims in El Paso County, Colorado, 1989–1990. *Accident Analysis and Prevention, 27*(3), 363–370.

Glimm, J., & Fenton, R. E. (1980). An accident-severity analysis of a uniform-spacing headway policy. *IEEE Transactions of Vehicular Technology, 29*(1), 96–103.

Goldstein, J. P. (1986). The effect of motorcycle helmet use on the probability of fatality and the severity of head and neck injuries. *Evaluation Review, 10*, 355–375.

Hutchinson, T. P. (1986). Statistical modeling of injury severity, with special reference to rider and front seat passenger in single-vehicle crashes. *Accident Analysis and Prevention, 18*(2), 157–167.

Hurt, H. H., Ouellet, J. V., & Thom, D. R. (1981). *Motorcycle accident cause factors and identification of countermeasures. Volume I: Technical Report* (Contract No. DOTHS-5-01160). Washington, DC: National Highway Traffic Safety Administration.

Jones, I. S., & Whitfield, R. A. (1988). Predicting injury risk with "new car assessment program" crashworthiness ratings. *Accident Analysis and Prevention, 20*(6), 411–419.

Lassarre, S. (1986). The introduction of the variables "traffic volume," "speed" and "belt-wearing" into a predictive model of the severity of accidents. *Accident Analysis and Prevention, 18*(2), 129–134.

Lui, K. J., McGee D., Rhodes P., & Pollock, D. (1988). An application of a conditional logistic regression to study the effects of safety belts, principal impact points, and car weights on riders' fatalities. *Journal of Safety Research, 19*, 197–203.

Luna, G. K, Maier R. V., Sowder L., Copass M. K., & Oreskovich, M. R. (1984). The influence of ethanol intoxication on the outcome of injured motorcyclists. *Journal of Trauma, 24*, 695–699.

Mannering, F. L., & Grodsky, L. (1994). Statistical analysis of motorcyclists' perceived accident risk. *Accident Analysis and Prevention, 26*(6), 21–31.

McFadden, D. (1981). Econometric models of probabilistic choice. In Manski & D. McFadden (Eds.), *Structural analysis of discrete data with econometric applications*. Cambridge, MA: The MIT Press.

Murdock, M. A., & Waxman, K. (1991). Helmet use improves outcomes after motorcycle accidents. *Western Journal of Medicine, 155*, 370–372.

Nelson, D., Sklar, D., Skipper, B., & McFeeley, P. J. (1992). Motorcycle fatalities in New Mexico: The association of helmet nonuse with alcoholic intoxication. *Annals of Emergency Medicine, 21*(3), 279–283.

Peltzman, S. (1975). The effects of automobile safety legislation. *Journal of Political Economy, 83*, 667–725.

Shankar, V. N., Mannering, F. L., & Barfield, W. (1995). Effect of roadway geometrics and environmental conditions on rural accident frequencies. *Accident Analysis and Prevention, 27*(3), 371–390.

Shankar, V. N., Mannering, F. L., & Barfield, W. (in press). Statistical analysis of accident severity on rural freeways. *Accident Analysis and Prevention.*

Shao, S. P. (1987). Estimating car rider injury severity in car/tractor-trailer collisions. *Accident Analysis and Prevention, 19*(3), 207–217.

Small, K. A., & Hsiao, C. (1985). Multinomial logit specification tests. *International Economic Review, 26*, 619–627.

Waller, P. F, Stewart J. R., Hansen A. R., Stutts J., Popkin C. L., & Rodgman, E. (1985). The potentiating effects of alcohol on driver injury. American Association of Automotive Medicine, Proceedings of 29th Annual Meeting, Morton Grove, IL.

Watson, G. S., Zador, P. L., & Wilks, A. (1980). The repeal of helmet use laws and increased motorcyclist mortality in the United States. *American Journal of Public Health, 70*, 579–585.

Weiss, A. A. (1992). The effects of helmet use on the severity of head injuries in motorcycle accidents. *Journal of the American Statistical Association, 87*, 48–56.

NOMENCLATURE

E	elasticity.
I	index of the set of possible accident severities.
$P_n(i)$	probability that accident n is severity i.
P	denotes probability statement.
S_{in}	is a function of covariates that determine the likelihood of accident n being of severity i.
X_n	the vector of measurable characteristics that determine the accident severity of accident n.
β_i	the vector of estimable coefficients for accident severity i.
ε_{in}	an error term that accounts for unobserved factors influencing accident n with severity i.