Factors Influencing Bicycle Crash Severity on Two-Lane, Undivided Roadways in North Carolina

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Concern over crashes involving bicycles and motor vehicles is largely due to the severity of injuries. The impacts of physical and environmental factors on the severity of injury to bicyclists are examined. North Carolina Highway Safety Information System crash and inventory data for state-controlled, two-lane, undivided roadways are analyzed. The injury severity distribution, measured on the KABCO scale, is as follows: no injury, 1.8 percent; complaint of pain, 24.4 percent; nonincapacitating injury, 42.5 percent; incapacitating injury, 25.5 percent; and fatal injury, 5.9 percent. The total number of involvements in this data set was 1,025, with a majority of the involvements occurring outside urbanized areas (80.5 percent). Using the ordered probit model, the effect of a set of roadway, environmental, and crash variables on injury severity is explored. Variables that significantly increase injury severity include straight grades, curved grades, darkness, fog, and speed limit. Higher average annual daily traffic, an interaction of speed limit and shoulder-width variables, and dark conditions with street lighting significantly lower injury severity. Separate models are estimated for rural and urban locations. Marginal effects of each factor on the likelihood of each injury-severity class are reported. Policy implications and possible countermeasures are then discussed.

Although in the United States only 2 percent of all motor-vehicle deaths are bicyclists, 813 bicyclists were killed in crashes in 1997 alone (*1*). Urban areas have received the most attention in the literature, but 36 percent of all national fatalities occurred in rural areas in 1997 (*1*). The interaction between motorists and cyclists on public roadways has been the subject of increased policy debate in the years following the passage of the Intermodal Surface Transportation Efficiency Act of 1991. An important component of this discussion relates to cyclist safety and reducing the risk of injury to users of this mode. While work has been done to describe crash types and the characteristics of the roadways, vehicles, and people involved in crashes, analysis of the factors influencing injury severity is scarce. Because of the complex nature of bicycle-motor vehicle crashes, understanding the specific factors and their relative influence on levels of injury severity is useful. This can be accomplished using ordered probability models, given that injury severity is measured on the KABCO scale in police reports. As transportation planners and engineers have opportunities to improve facilities to serve alternate-mode choices such as bicycles, this analysis can be especially useful in the selection and design of facilities that not only will help to reduce crash incidence but also injury severity.

This analysis seeks to examine the influence of roadway and crash variables on injury severity in bicycle-motor vehicle crashes on state-controlled, two-lane roadways in North Carolina from 1990 through 1993. Over the 4 years examined in this data set, 60 bicyclists were killed in North Carolina and 947 were injured in police-reported bicycle-motor vehicle crashes. Additionally, North Carolina maintains a system of State Bicycle Routes of more than 3600 km (2,250 mi), 90 to 95 percent of which is on two-lane, undivided roadways in rural areas (according to M. Meletiou and T. Norman, North Carolina Department of Transportation: Bicycle and Pedestrian Division). Relatively good-quality data related to the crashes on these roadways were available from FHWA's Highway Safety Information System (HSIS) database, which is used for analysis. The North Carolina Division of Highways maintains a particularly extensive roadway inventory system for 123 200 km (77,000 mi) of roadway, representing a very high proportion of the total kilometers existing in the 147 000 state km (92,000 state mi). Approximately 55 680 km (34,800 mi) have been entered into a computer mileposting system, so crashes can be linked to them (*2*). Also, there are no county-maintained roadways in North Carolina, so most rural roadways are contained in the data set used in this study.

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LITERATURE REVIEW

The definitive early work in the field of bicycle safety by Cross and Fisher (*3*) served to identify crash types and median ages of the cyclists involved and the severity of injury (fatal or nonfatal) in each crash type. The results especially were useful in targeting educational programs toward age groups that were overrepresented in certain crash types.

Additional federal research in the early 1980s focused on cyclist behavior, analysis of specific crash types such as right-turn-on-red situations, and development of countermeasures (*4–7*). Stutts et al. (*8*) review these efforts as well as a considerable number of safety education efforts undertaken both by nongovernmental organizations and a number of states in the 1980s.

Considerable work has been done by FHWA to compile descriptive statistics on both pedestrian and bicycle crash types. In the FHWA-sponsored report *Pedestrian and Bicycle Crash Types of the Early 1990's* (*9*), Hunter et al. analyzed hard copies for 3,000 bicycle-motor vehicle crashes from six states and linked 2,990 of them with computerized state police report files. The major findings are as follows: Intersections, driveways, and other junctions account for three-quarters of all crashes. Children under 15 are overrepresented and adults 25 to 44 and 65-plus are underrepresented in crashes, but those 44-plus are overrepresented in fatalities. Eighteen percent of all bicycle involvements are serious or fatal (A + K on the KABCO scale). Alcohol or drug use is present in about 5 percent of crashes overall, but it is 15 percent for the 25-to-44 group and is more frequent on weekends and in hours of darkness. Two-thirds of the involvements occur during late afternoon and early evening (exposure is quite high and visibility can be a problem during these times). Two-thirds of the involvements are urban, and 7 percent are on private property. Ages 10 and under are overrepresented in driveways, alleys, and parking lots. About 60 percent of the involvements occur on two-lane roadways, and roads with narrower lanes and higher speed limits are associated with more than their share of serious and fatal injuries to bicyclists.

Research related to facility location, selection, and design for bicyclists still is developing. The AASHTO 1984 "Green Book" recommends paved shoulders; wide outside traffic lanes of 4.57 m (15 ft) minimum; bicycle-safe drain grates; and maintenance of smooth, clean riding surfaces (*10*). More specific guidelines are available in the 1991 AASHTO *Guide for the Development of New Bicycle Facilities* (*11*). On the subject of lane widths, McHenry and Wallace (*12*) found that in multilane highways, optimal lane width was greater than 4.17 m (13 ft 8 in.) and less than 5.18 m (17 ft). A 1994 FHWA-sponsored study tour of England, Germany, and the Netherlands examined pedestrian and bicyclist safety conditions (*13*). They found that reduced vehicle speeds were of major importance to bicyclist and pedestrian safety, in addition to restricted traffic movement and reduced travel distances. Specific facility-related bicycle safety measures also are discussed, though primarily in an urban context.

Relevant exposure data are often not available, and there is a clear need for collecting such data in bicycle safety research. In a recent paper examining exposure and safety on roads, off-road paths, and sidewalks, L. Aultman-Hall and M. G. Kaltenecker of the University of Kentucky found that the rate of major injuries was highest on sidewalks and off-road paths, compared to on-road cycling. The analysis also demonstrates one method for quantifying bicycle travel exposure rates. Assessing the level of risk associated with particular locations, behaviors, and conditions is difficult without information about how many cyclists are uninjured as well as injured. This analysis will focus on factors influencing severity once a crash occurs.

DATA DESCRIPTION AND HYPOTHESES

In this study, it is assumed that for crashes involving a motor vehicle and a bicycle, the cyclist is more severely injured (98 percent of drivers sustained no injury in the 2,990 cases examined by FHWA's *Pedestrian and Bicycle Crash Types of the Early 1990s*). The significant difference in mass between the motor vehicle and the bicycle, as well as the protection afforded the motorist by the physical structure of the vehicle, also contribute to increased injury severity for the cyclist compared to the motorist. Therefore, the severity variable, representing the worst injury in the crash, is assumed to refer to the cyclist.

Roadway and environmental factors as well as individual, vehicle, and bicycle factors drive the collision process. During a crash event, the energy transfer determines injury severity in the collision and possible fall from the bicycle, along with the medical care that is subsequently administered. Motorist and cyclist reaction times, perception and judgment errors, and attention also affect the collision process. Information processing of both the bicyclist and the driver, the care that some drivers use when near bicyclists, and the risk-taking behaviors of motorist and cyclist also may increase or decrease injury severity.

Although the literature classifies more than 80 crash types (*9*), the HSIS data set used for this analysis does not disaggregate by crash type. Additionally, in this data set, no information is collected on bicycle characteristics, and individual characteristics are limited to age, gender, and race on the crash reporting form. Detailed information about roadway and environmental characteristics, however, is gathered for all crashes. The severity of injury is expected to increase with the motorist's lack of awareness of the cyclist and inability to maneuver because of roadway or environmental characteristics. Additionally, while driver and cyclist characteristics as well as vehicle characteristics may contribute to increased or decreased severity, this analysis is limited to physical and environmental characteristics. Since the roadway characteristics are policy sensitive, they are examined most closely in this study. Variables expected to significantly influence injury severity among cyclists and the reasoning behind the expectations are listed in Table 1. Each variable is assumed to temporally precede the injury itself. The ordered probability model used to analyze injury severity examines the statistical correlation underlying the hypotheses.

The 1990–1993 HSIS data for collisions between motorists and cyclists on two-lane roadways in North Carolina are used for analysis (N = 1,025). HSIS includes police-reported data about crashes, occupants, vehicles, roadway, and environment. This analysis is limited to the roadway and crash variables because some of these are policy sensitive (Table 2). Additionally, the data are limited to the two-lane, undivided roadway class since these make up the majority of the state-maintained bicycle routes and since bicycle crash data are sparse for the other roadway classes.

Approximately 23 percent of the undivided highways in this North Carolina data set have unknown right-shoulder widths. Furthermore, the left-shoulder-width variable is intended to measure the width of the inside shoulder on a divided highway, but even with only two-lane, undivided roadways, a surprising number of samples had values for the left-shoulder width. (In this data set, 93.75 percent of the shoulder-width values were the same for the right and left shoulders.) This refers to the shoulder width on the opposite side of the two-lane roadway. Therefore, the left-shoulder-width variable was not used in this analysis. Despite the missing data (238 cases), right-shoulder width was included as a policy variable of interest.

MODELING METHODOLOGY

The ordered probit model is especially useful for analysis of injury severity. Injury severity data are categorical and ordinal. As a multivariate model, ordered probit accounts for interdependencies among explanatory variables, and the marginal effects of significant variables can be used to examine the degree to which different factors influence the severity class of injury. Additionally, ordered probit can represent unequal differences between categories in the dependent variable for each significant factor. In other words, it does not assume that the difference between the first and second injury class is the same as the difference between the fourth and fifth class. For a detailed discussion of the model, see O'Donnell and Connor (*14*) or Duncan et al. (*15*). In the HSIS NC file, injury severity is coded using the KABCO system:

- K for fatal injury;
- A for incapacitating injury;
- B for nonincapacitating injury;
- C for no visible injury, but complaint of pain; and
- O for no injury, property damage only.

TABLE 1 Roadway/Environmental Variables and A Priori Expected Influence on Injury Severity in Bicycle Crashes

Variable	Effect on Motorist	Effect on Cyclist	Expected Influence
Curves	Curves decrease motorist control of vehicle; may limit visibility; centrifugal acceleration may increase force of impact.	Curves decrease bicyclist control; may limit visibility.	Increased severity
Grades	Contributes to higher speed differential and impaired braking and accelerating of the vehicle.	Contributes to impaired braking and accelerating of bicycle and less control of bicycle.	Increased severity
Intersection or Driveway	Intersections provide more opportunities for conflict and unexpected behaviors; slower vehicular speed.	Intersections provide more opportunities for conflict and unexpected behaviors.	Increase/decrease severity
Right Shoulder Width	Presence of right shoulder may allow more visibility for the motorist.	Presence of right shoulder may allow more visibility for the cyclist; increased room for evasive action.	Increase/decrease severity
Average Annual Daily Traffic	Higher AADT implies that traffic congestion is likely, resulting in lower vehicular speeds and slower impacts.	Congestion and more traffic may contribute to more cautious cycling in the face of traffic, and slower impacts.	Decreased severity
Speed Limit	Higher vehicular speeds increase force of impact.	Higher vehicular speeds increase force of impact.	Increased severity
Darkness	Darkness decreases motorist visibility and therefore reaction time, allowing less time for evasive action and higher speed differentials at impact.	Darkness decreases cyclist visibility and therefore reaction time, allowing less time for evasive action and higher speed differentials at impact.	Increased severity
Lighted Darkness	Lighting of roadway compensates for decreased visibility and may mean lower impact speeds.	Lighting of roadway can reduce the effect of darkness.	Increase/decrease severity
Rain	Rain reduces visibility for the motorist and wet surfaces decrease vehicular control; cautious driving may decrease motorist speeds and force of impact.	Rain may contribute to more cautious cycling, and slower impacts; decreases bicyclist's visibility, control, and braking.	Increase/decrease severity
Fog	Fog reduces visibility for the motorist; cautious driving may decrease motorist speeds and force of impact.	Fog may contribute to more cautious cycling, and slower impacts; decreases bicyclist's visibility.	Increase/decrease severity

The ordered probit model has the following form:

$$y^* = \boldsymbol{\beta}'\mathbf{x} + \epsilon \qquad (1)$$

where

- y^* = the dependent variable (injury severity that is unobserved),
- $\boldsymbol{\beta}'$ = the vector of estimated parameters,
- $\mathbf{x}$ = the explanatory variables, and
- ϵ = the normally distributed error term.

Parameter estimates ($\boldsymbol{\beta}$) represent the effect of explanatory variables on the underlying injury scale. Only the signs, relative magnitudes, and significance of the parameter estimates can be interpreted directly; separate computation of the marginal effects for each independent variable is needed to understand the effect of a unit change in the independent variable. Based on this specification, the probability of the dependent variable falling in any ordered category is

$$\text{Prob}(y = n) = \Phi(\mu_n - \boldsymbol{\beta}'\mathbf{x}) - \Phi(\mu_{n-1} - \boldsymbol{\beta}'\mathbf{x}) \qquad (2)$$

ϵ has a cumulative distribution denoted by $\Phi(\cdot)$ and density function denoted by $\phi(\cdot)$. An individual falls in category n if $\mu_{n-1} < y^* < \mu_n$; the injury data y are related to the underlying latent variable y^* through thresholds μ_n. For the five-point KABCO scale, $n = 1, \ldots, 4$. That is, $\mu_0 = 0$ and $\mu_4 = +\infty$ and $\mu_1 < \mu_2 < \mu_3$ are defined as three thresholds among which categorical responses are estimated. The estimation of this model is relatively simple; the likelihood function can be derived easily. Ordered probit estimation will give the thresholds μ and parameters $\boldsymbol{\beta}$.

The thresholds μ show the range of the normal distribution associated with the specific values of the response variable. The remaining parameters $\boldsymbol{\beta}$ represent the effect of changes in explanatory variables on the underlying scale. The marginal impacts of factors $\mathbf{x}$ on the underlying injury propensity can be evaluated as

$$\partial\text{Prob}(y = n)/\partial x = -[\phi(\mu_n - \boldsymbol{\beta}'\mathbf{x}) - \phi(\mu_{n-1} - \boldsymbol{\beta}'\mathbf{x})]\boldsymbol{\beta} \qquad n = 1, \ldots, 4 \qquad (3)$$

Computation of marginal effects is particularly meaningful for the ordered probit model in which the effect of variables $\mathbf{x}$ on the intermediate categories is ambiguous if only the parameter estimates are available.

Goodness of fit for an ordered probit model can be obtained by

$$\rho^2 = 1 - [\ln L_b / \ln L_0] \qquad (4)$$

Table 2 Relevant HSIS Variables from Roadway and Crash Files

Variable	Description	Categories	Frequencies (1025 cases) N	%
AADT	Average Annual Daily Traffic	00000= unknown	1	0.10%
		00001-00100=0-100	9	0.88%
		00101-00500=101-500	58	5.66%
		00501-01000=501-1000	98	9.56%
		01001-02000=1001-2000	175	17.07%
		02001-05000=2001-5000	261	25.46%
		05001-10000=5001-10000	255	24.88%
		10001-15000=10001-15000	120	11.71%
		15001-20000=15001-20000	39	3.80%
		20001-40000=20001-40000	8	0.78%
		40001-99999=40000+	1	0.10%
LIGHT	Light Condition	0=not stated	5	0.49%
		1=daylight	757	73.85%
		2=dusk	56	5.46%
		3=dawn	5	0.49%
		4=dark, St lit	65	6.34%
		5=dark, not lit	137	13.37%
RD_CHAR1	Road Character	0=not stated	5	0.49%
		1=straight, level	701	68.39%
		2=straight, hill-crest	48	4.68%
		3=straight, grade	148	14.44%
		4=straight, bottom	16	1.56%
		5=curve, level	58	5.66%
		6=curve, hill-crest	6	0.59%
		7=curve, grade	39	3.80%
		8=curve, bottom	4	0.39%
RSHLDWID	Right Shoulder Width	0=unknown	238	23.22%
		1-3=1-3 ft	92	8.98%
		4-6=4-6	479	46.73%
		7-9=7-9	135	13.17%
		10-13=10-13	71	6.93%
		14-25=14+	10	0.98%
		26=no parking	0	0.00%
		27=parallel park	0	0.00%
		28=angle parking	0	0.00%
RURURB	Rural-Urban Identification	0=outside urbanized	921	89.85%
		1=unique small urban	47	4.59%
		2=unique urbanized	40	3.90%
		3=other small urban	17	1.66%
		4=other urbanized	0	0.00%
SEVERITY	Worst Injury in Crash	1=no injury	18	1.76%
		2=class C	250	24.39%
		3=class B	436	42.54%
		4=class A	261	25.46%
		5=fatal injury	60	5.85%
SPD_LIMT	Speed Limit	20 mph	16	1.56%
		25 mph	12	1.17%
		30 mph	6	0.59%
		35 mph	344	33.56%
		40 mph	2	0.20%
		45 mph	118	11.51%
		50 mph	3	0.29%
		55 mph	524	51.12%
TRF_CNTL	Traffic Control Type	00=not stated	10	0.98%
		01=stop sign	152	14.83%
		02=yield sign	4	0.39%
		03=stop&go signal	70	6.83%
		04=flash sign & stop	0	0.00%
		05=flashing signal	2	0.20%
		06=rr gate & flasher	1	0.10%
		07=rr flasher	0	0.00%
		08=rr crossbucks	0	0.00%
		09=human control	2	0.20%
		10=other	2	0.20%
		11=no control	782	76.29%
WEATHER	Weather Condition	0=not stated	4	0.39%
		1=clear	825	80.49%
		2=cloudy	150	14.63%
		3=raining	43	4.20%
		4=snowing	0	0.00%
		5=fog, smog, smoke, dust	3	0.29%
		6=sleet or hail	0	0.00%

where

L_b = the log-likelihood at convergence,
L_0 = the log-likelihood at 0, and
ρ^2 = range of 0 to 1.

As ρ^2 increases, the model fit improves, though the values do not have a "natural interpretation" (Greene, *16*).

FINDINGS

Overview

The injury severity distribution measured on the KABCO scale is as follows: no injury = 18 (1.8 percent); complaint of pain = 250 (24.4 percent); nonincapacitating injury = 436 (42.5 percent); incapacitating injury = 261 (25. 5 percent); fatal injury = 60 (5.9 percent). The total number of involvements was 1,025. A majority of involvements occurred outside urbanized areas (80.5 percent).

Most involvements occurred in daylight (73.9 percent), but 13.4 percent occurred at night on unlighted sections and 6.3 percent at night on lighted sections. Involvements occurring at dawn were 5.5 percent, and .5 percent occurred at dusk. Clear conditions accounted for 80.5 percent of all involvements, 14.6 percent occurred in cloudy conditions, 4.2 percent were coded as rainy conditions, and less than 1 percent occurred in snow, fog, smog, sleet, or hail.

The mean annual average daily traffic (AADT) for these two-lane roads was 5,186, representing relatively low-volume roads. Speed limits ranged from 32.2 km/h (20 mph) to 88.6 km/h (55 mph), with most of the involvements occurring on 88.6-km/h (55-mph) sections (51.1 percent), followed by 56.4-km/h (35-mph) sections (33.6 percent) and 72.5-km/h (45-mph) sections (11.5 percent). As mentioned earlier, right-shoulder width is unknown for 12 percent of the North Carolina HSIS mileage, and in this sample, 238 cases (23.2 percent) are unknown. The remaining cases are distributed between 0.3 m (1 ft) and 4.6 m (15 ft), with 65.9 percent of all cases between 0.6 and 2.4 m (2 to 8 ft), and with 1.8 m (6 ft) accounting for 20.9 percent of the cases and 1.2 m (4 ft) accounting for 15.8 percent.

Modeling Results

Two injury-severity ordered probit models are presented (Table 3), one with all cases (N = 1,025) and one restricted to rural cases (N = 921). Some differences exist between the two specifications and the results. The rural-only sample is discussed in detail. Urban cases alone

Table 3 Ordered Probit Models of Injury Severity with Urban Cases and Without Urban Cases

Variable	Coefficients with Rural and Urban	Z-statistics with Rural and Urban	Coefficients Rural Only	Z-Statistics Rural Only
Average annual daily traffic divided by 1000⁺	-.0158	-1.899	-.0173	-1.981
Speed Limit⁺	.0086	1.664	.0085	1.557
Intersection (including driveways)	.0541	.705	.0301	.376
Right Shoulder Width	.0262	1.349	.0215	1.016
Right Shoulder Width Unknown	-.1936	-1.288	-.1527	-.960
Speed Limit * Right Shoulder Width⁺	-.0054	-1.786	-.0035	-1.071
Fog*	1.2255	2.415	1.2253	2.448
Dark, Lighted⁺	-.2181	-1.553	-.2356	-1.652
Dark*	.2550	2.629	.2573	2.419
Straight, hill-crest	.1488	.863	.1975	1.118
Straight, grade*	.2360	2.405	.2581	2.375
Straight, bottom	.3770	1.270	.3616	1.189
Curve, level	.0120	.084	-.0129	-.085
Curve, hill-crest	.6460	.714	.6365	.721
Curve, grade*	.3660	2.008	.4440	2.246
Curve, bottom	.0144	.044	-.0072	-.022
Year = 1993	-.3179	-3.429	-.2619	-2.645
Year = 1992	-.1820	-1.847	-.1586	-1.518
Year = 1991	-.1471	-1.552	-.1222	-1.224
μ_0 (Constant)	2.0286	7.575	2.0165	7.325
μ_1	1.5172	14.569	1.5583	13.435
μ_2	2.6825	24.574	2.7215	22.419
μ_3	3.8037	30.993	3.8572	28.504
Observations	**1025**		**921**	
Log Likelihood	**-1293.920**		**-1156.907**	
Restricted Log Likelihood	**-1325.515**		**-1187.434**	
ρ^2	**.024**		**.026**	

* Significant at .05 confidence level
⁺ Significant at .1 confidence level

($N = 104$) could not be compared to the other two models because of insufficient cases for all variables.

A z-statistic of ±1.96 or greater indicates that a given variable significantly influences injury severity at 95 percent confidence or higher. Variables with z-statistics between ±1.64 and ±1.96 are significant at greater than 90 percent confidence but less than 95 percent confidence. Positive signs on significant explanatory variable coefficients indicate that the variable increases severity and vice versa.

For the rural-only model, $\rho^2 = .026$, and for the entire sample $\rho^2 = .024$, indicating relatively low goodness of fit. The rural-only model identified six variables that were significantly associated with injury severity in bicycle-motor vehicle crashes on two-lane roadways in rural areas. The marginal effects of each significant explanatory variable on each severity level are listed in Table 4. Roadway characteristics contributing to increased injury severity include straight grades and curved grades. Environmental characteristics contributing to increased injury severity include foggy conditions and dark, unlighted conditions.

Involvements on both straight grades and curved grades were found to be significantly more severe than the base of straight-level sections. Other variables including straight hill crest, straight bottom, curved level, curved hill crest, and curved bottom were statistically insignificant, but are included in the model (*a*) for demonstration, (*b*) to prevent them from becoming part of the "base," and (*c*) because they theoretically can influence severity by decreasing visibility and maneuverability. Both straight grades and curved grades were significant at greater than a 95 percent confidence level. The magnitude of the curved-grade coefficient was larger than that of the straight-grade variable, suggesting that decreased vehicle control for the motorist and bicycle control for the cyclist as well as increased speed differentials associated with grades may compound injury severity. Braking and acceleration can be impaired on all grades and avoidance opportunities may be relatively limited on curved grades, leading to larger speed differentials. Larger speed differentials can lead to higher collision speeds and greater transfer of energy, resulting in increased injury severity. Drivers and bicyclists may compensate by going slower on straight grades and curved grades, but they do not seem to slow down enough to reduce injury severity compared with crashes that occur on straight levels.

Involvements at intersections (including driveways) did not significantly increase injury severity. Shoulder width of any size was found to have no statistically significant effect on severity compared to the absence of a shoulder. Separating "zero" shoulder width from others was complicated by the coding system (a zero response is coded as an unknown shoulder width). Shoulder widths of 0.3 to 0.9 m (1 to 3 ft) did not have a statistically significant influence on injury severity compared to all shoulder widths of greater than 0.9 m (3 ft). An interaction of the speed-limit and shoulder-width variables, however, revealed a significant decrease in injury severity (90 percent level of confidence) in the model that included all cases. This suggests that as speed limit increases, the presence of a shoulder

Table 4 Marginal Effects in Injury Severity Ordered Probit Model with Rural Only

Variables	Marginal Effect; No injury (O)	Marginal Effect; Complaint of pain (C)	Marginal Effect; Non-incapacitating injury (B)	Marginal Effect; Incapacitating injury (A)	Marginal Effect; Fatal (K)	Mean
μ_0 (Constant)	-0.107	-0.6199	0.103	0.4782	0.1457	
Average annual daily traffic (N/1000)	0.0009	0.0053	-0.0009	-0.0041	-0.0012	5.314
Speed Limit (mph)	-0.0005	-0.0026	0.0004	0.002	0.0006	45.35
Intersection (including driveways) = 1 else 0	-0.0016	-0.0093	0.0015	0.0072	0.0022	0.383
Right Shoulder Width (ft)	-0.0011	-0.0066	0.0011	0.0051	0.0016	4.453
Right Shoulder Width Unknown = 1 else 0	0.0081	0.0469	-0.0078	-0.0362	-0.011	0.248
Speed Limit * Right Shoulder Width	0.0002	0.0011	-0.0002	-0.0008	-0.0003	32.89
Fog = 1 else 0	-0.065	-0.3767	0.0626	0.2906	0.0885	0.003
Dark, Lighted = 1 else 0	0.0125	0.0724	-0.012	-0.0559	-0.017	0.069
Dark = 1 else 0	-0.0137	-0.0791	0.0131	0.061	0.0186	0.136
Straight, hill-crest = 1 else 0	-0.0105	-0.0607	0.0101	0.0468	0.0143	0.047
Straight, grade = 1 else 0	-0.0137	-0.0793	0.0132	0.0612	0.0186	0.138
Straight, bottom = 1 else 0	-0.0192	-0.1112	0.0185	0.0858	0.0261	0.014
Curve, level = 1 else 0	0.0007	0.004	-0.0007	-0.0031	-0.0009	0.058
Curve, hill-crest = 1 else 0	-0.0338	-0.1957	0.0325	0.1509	0.046	0.007
Curve, grade = 1 else 0	-0.0236	-0.1365	0.0227	0.1053	0.0321	0.037
Curve, bottom = 1 else 0	0.0004	0.0022	-0.0004	-0.0017	-0.0005	0.004
Year = 1993 = 1 else 0	0.0139	0.0805	-0.0134	-0.0621	-0.0189	0.266
Year = 1992 = 1 else 0	0.0084	0.0488	-0.0081	-0.0376	-0.0115	0.245
Year = 1991 = 1 else 0	0.0065	0.0376	-0.0062	-0.029	-0.0088	0.237

significantly decreases injury severity in the event of a crash. In the rural-only model, the variable was not significant.

Higher AADT was found to be significantly associated with decreased injury severity in the event of a crash. This may be due to lower speeds in congested conditions. Higher speed limits did not significantly affect injury severity in the rural-only model but did significantly increase severity in the model with all cases (90 percent level of confidence). It is possible that cyclists use more caution when they know that there are many motor vehicles that can potentially hit them. Motorists also might use greater caution when they expect bicyclists.

Injuries are more severe in foggy conditions compared to clear conditions, perhaps because of decreased reaction distance and increased closing speed resulting from low visibility. The large parameter associated with foggy conditions relative to other weather variable coefficients implies high injury risk, given a crash.

Dark, unlighted conditions also increased injury severity relative to daylight conditions, again perhaps due to decreased visibility and decreased reaction distance for both the motorist and the bicyclist. Lighted sections significantly decreased severity relative to daylight (90 percent confidence level) in the rural-only model. Street lighting therefore decreases the severity of injury compared with dark conditions in rural areas. Moreover, emergency crews might take longer to respond to crashes on dark, unlit roadways.

The significant changes between the two models when urban involvements were removed have been discussed, but it also should be noted that urban crashes are generally underrepresented in the sample. The rural-urban distinction is based on the census definition of "urbanized areas," in which all incorporated towns of less than 5,000 population are classified as rural unless they are located adjacent to a larger urbanized area. Additionally, no statistically significant effect on severity was seen when urban crashes were compared to rural crashes by adding an urban-rural variable to the model.

Interestingly, the model revealed a significant decrease in injury severity in crashes occurring in 1993 and a general trend of decreasing severity over the three years represented (using 1990 as the "base" year). This result is consistent with an overall decrease in crash severity for the entire HSIS crash file.

The marginal effects of significant variables are listed in Table 4. These show how severity probabilities change with a unit change in the explanatory variable while holding all other variables at their means. An increase in AADT from the mean value of 5,314 to 6,314 is associated with an increased chance of a no-injury crash, $P[O] = .09$ percent, and of minor injury, $P[C] = .53$ percent. This increased chance is accounted for by the change in the other categories, that is, $P[B] = -.09$ percent; $P[A] = -.41$ percent; and $P[K] = -.12$ percent. Although rare, crashes in fog are highly injurious, with a 29 percent rise in the chances of severe injury and an 8 percent increase in the chances of a fatality, given a crash. The marginal effects indicate that curved grades are about twice as likely to result in a fatal crash as straight grades are. (There is a 4.8 percent increase in fatalities on curved grades compared to a 2.6 percent increase on straight grades—both relative to straight-level roads.)

There are important implications of these findings for the selection of state-maintained bicycle routes. As mentioned earlier, North Carolina maintains a system of State Bicycle Routes of more than 3600 km (2,250 mi), 90 to 95 percent of which are on two-lane, undivided roadways in rural areas. The selection of these state-maintained bicycling highways is based primarily on the level of vehicular traffic and scenery. That is, decision makers choose relatively lightly traveled roadways that also are scenic. Given that both crash occurrence and injury severity should be important considerations in route selection, this analysis indicates that additional criteria related to roadway and environmental characteristics are important. In addition to vehicular traffic and scenery, decision makers also should review the frequency of straight grades and curved grades on the road segments, the presence of street lighting, the presence of a shoulder, the speed limit, and the presence of foggy conditions in selecting State Bicycle Routes. Another implication of this study is that reducing grades and curves in new two-lane roadway construction might have additional benefits in terms of reduced bicycle crash severity.

Potential Biases and Caveats

Reporting bias often is a problem with severity analysis. Property-damage-only (PDO) or no-injury crashes often are underreported. In this analysis, however, given that the cyclist is likely to get injured and may be more likely to report the crash, the underreporting of PDO (if any) is less of a concern.

Note that the cases studied are all bicycle-motor vehicle involvements and the cyclist-only collisions are not analyzed. For example, a cyclist who runs off the road but never collides with a motor vehicle is not included in the database. Also, crashes that occur on non-state-controlled roadways are excluded (e.g., those that occur on private driveways) as well as those that occur on other roadway classes. Although these exclusions do not create a bias, they limit the scope of the analysis and the generalizability of the findings.

Additional analysis of vehicle and personal variables available from the HSIS data set could isolate some of the potential exposure bias that may be present in the sample. For example, including age in the injury-severity model can control for the effect of age. Also, if age is correlated with a specific explanatory variable currently in the model, then the statistical significance and coefficient of that variable potentially can change.

Although we do not have a direct measure of bicycle exposure in the injury-severity model, this is not a problem. The dependent variable is injury severity given a crash, and not crash occurrence.

CONCLUSION

This study examined the effect of roadway and environmental factors on injury severity in bicycle-motor vehicle collisions. An ordered probit model for injury severity was estimated using the HSIS data set for two-lane roadways. The model parameters and the marginal effects of significant variables were used to examine the influence of roadway and crash characteristics on injury severity of cyclists.

Roadway characteristics that increased severity were speed limit, straight grades, and curved grades, again likely related to driver- and cyclist-impaired braking, acceleration, and maneuverability. Environmental factors including fog and unlighted darkness increased injury severity, most likely related to their effect on driver reaction time and speed differentials at the point of impact. Average annual daily traffic, an interaction of the shoulder-width and speed-limit variables, and street lighting were associated with decreased injury severity.

Countermeasures based on these findings—such as providing shoulders and street lights on two-lane roadways where bicycling activity exists and encouraging bicyclists to avoid fog and/or wear gear that enhances visibility in fog—should be examined more deeply. Since only involvements on state-controlled, two-lane roads in North Carolina were examined, representing a small portion of all bicycle crashes in primarily rural areas, these results should be applied to relatively similar roadway types and areas. It also should be noted, however, that these findings were not significantly different for the urban crashes included in the data set. Additionally, these findings can inform route selection, signage decisions, and safety education efforts related to the "Bicycling Highways" system in North Carolina and bicycle routes on similar roadways elsewhere. Both crash occurrence and injury severity should be important considerations in selection of state-maintained bicycle highway routes. This analysis indicates that in addition to vehicular traffic and scenery, decision makers also should review the frequency of straight grades and curved grades on the road segments, the presence of street lighting, the speed limit, the presence of a shoulder, and the presence of foggy conditions in selecting State Bicycle Routes. Another implication of the results is that reducing grades and curves in new two-lane roadway construction might have additional benefits in terms of reduced bicycle crash severity.

Additional research is required to examine the effect of vehicle and personal characteristics and behaviors (such as helmet use) on injury severity. Specific attention to the questions of roadway class, shoulder widths, and presence of traffic-control measures also should be examined.

ACKNOWLEDGMENTS

The Highway Safety Information System crash data were provided by the University of North Carolina Highway Safety Research Center. LIMDEP statistical software was used for estimation of the ordered probit models. The authors thank the federally sponsored Southeastern Transportation Center, University of Tennessee, for its support. They also are very grateful to Jane Stutts and the anonymous TRB reviewers for their constructive comments.

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Publication of this paper sponsored by Committee on Bicycling.