SEVERITY MODELS FOR ROADSIDE OBJECTS

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INTRODUCTION

Despite numerous safety improvements in motor vehicles and roadways, roughly 40,000 people are still killed and thousands more seriously injured in motor vehicle accidents each year. A considerable number are injured or killed in collisions with roadside objects such as trees, utility poles, and embankments. Approximately 16,000 deaths yearly are a result of accidents in which a vehicle runs off the roadway and rolls strikes a roadside object or rolls over (*1*). In order to reduce this number of accidents, roadway designers must have some method of determining which roadway designs are most likely to have accidents that result in serious or fatal injuries.

To compare the cost-effectiveness of different designs at a particular site a prediction of both the frequency and severity of accidents at that location is necessary. Methods have been developed and fairly well accepted to predict the frequency of accidents, but little confidence is placed in methods that are used to predict severity. Two general techniques have been developed for estimating severity -- severity indices and severity models. Both techniques result in a number that is representative of the severity of a collision with that object. Severity indices are typically single numbers assigned to each type of object that are indicative of the severity of a collision with that object. They do not reflect impact parameters such as speed and impact angle. A severity model does account for varying collision parameters. Existing severity models and indices for a given object typically represent either the probability of serious injury or a certain distribution of all types of injury. This paper discusses the existing models and indices and proposes new severity modelsfor roadside hazards. It does not specifically address models for estimating the frequency of accidents on roadways, but will discuss how the severity models can be used in conjunction with frequency models.

IDENTIFICATION OF PROBLEM

The majority of serious injuries in roadside accidents occur on state, county, or local roadways, not interstates. All of these entities have limited funds for safety considerations. Although state highways have minimum design standards based on safety considerations, they do not have objective methods of evaluating roadside design options outside the scope of the design standards. If several safety options are available at a particular site, there is no accurate way of measuring safety per dollar spent. The relative severity of striking different objects is uncertain, which makes it difficult to integrate cost-effectiveness into safety design beyond the scope of the design standards.

State and local roadway departments must also spend their limited funds on improvements of existing roadsides. Two different types of decisions must be made which might utilize severity models. First, the locations that need to be improved must be selected. Once the sites targeted for improvements are located, different design options must be evaluated. In both decisions the improvement in safety per dollar spent must be considered. Designers need an objective method of identifying the location with the most severe accidents. They also need an accurate predictor of severity in collisions with different roadside objects in order to compare different design improvements. A valid severity model for different roadside objects is needed for these decisions.

Another motivation for improving severity models is the increased emphasis by the federal government on highway safety. Several changes have been made in the funding and requirements for highways through the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). Funding has been increased for non-interstate roadways. Additionally, proposed funding specifically appropriated for improving highway safety has increased 20 percent from 1992 to 1993 (*2*). A minimum of 10 percent of all state highway funding must be spent on projects with safety benefits (*3*). These changes will lead to many rehabilitation projects. This new construction will provide opportunities for using an accurate severity model. In order to receive some of the funding in the ISTEA, safety management systems must be set up in each state [3]. An accurate method of evaluating roadway and roadside improvements will surely be an integral part of these systems. An improved

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severity model would, therefore, be an asset to these systems.

Several severity indices have already been developed. Many are based on expert opinion about which objects are most hazardous in collisions, but because they are based on judgement they are subject to criticism. Several measures of the severity of accidents with different roadside objects have been calculated using accident data, which are more objective, but the results have not been reliable due to unreported accidents and lack of detail in the data. Crash test data have also been used to develop severity models, but with limited success. With the current improvements in data on roadside accidents and new methods of developing severity models, more accurate and objective severity measures could be found. The following sections discuss the existing types of severity models and how they have been used.

EXISTING SEVERITY MODELS

Severity models are generally used in conjunction with frequency models to predict the number of injury accidents or the accident costs on a given roadway. A model which accounts for both accident frequency and severity is called a hazard model. The following section discusses the different measures of severity and how they fit into various hazard models.

Cost-Based Severity Models

Currently, the most common method of comparing roadside changes is by using a benefit-cost analysis. An estimate of the reduction in injuries and fatalities due to a proposed safety improvement is made. Dollar values are assigned to injuries and fatalities and then the cost savings from the reduction in injuries is computed. The ratio of dollars saved to dollars spent on improvements, or benefit-cost ratio, is computed for all alternatives and the ones with the highest ratios are implemented. A drawback to this method is that there is no consensus on accident costs because of the disagreements on the value of human life. One fatality ranges from $250,000 by the National Highway Traffic Safety Administration (NHTSA) to $1.5 million (1986 dollars) by the Federal Highway Administration (FHWA) (*4*) (*5*). When a large dollar value is used, the analysis becomes very sensitive to small changes in the severity index. A slight mistake in the severity index can mean a $100,000 difference or more in the benefit/cost analysis, making a certain alternative appear misleadingly expensive or cost effective. The assignment of a severity index will never be exact using this method and thus this type of error will not be infrequent.

The earliest severity models were developed for use in benefit-cost analyses. The accident costs were based on the severity of accidents. The first group of indices, developed by Weaver, et al in Texas in 1974 was based on engineering judgement (*6*). A questionnaire was sent to numerous professionals in highway safety design, operations, maintenance, law enforcement, and administration. The respondents were asked to agree or disagree with 98 statements regarding roadside hazards and also to rank the hazard potential of 52 roadside objects. This survey resulted in a relationship between a severity index and injury severity and also in a list of suggested severity indices for various roadside objects. The index, shown in Figure 1 ranged from 0 to 10, with 10 representing a certain fatality given an accident with that object had occurred. Figure 1 shows the injury distribution associated with each given severity level.

The earliest recommended use of these severity indices is in the 1977 American Association of Highway and Transportation Officials (AASHTO) Barrier Guide which presents a method of finding a benefit-cost ratio for roadway improvements (*7*). The accident costs were calculated from the severity index developed in the Texas survey. An assumed cost for each type of injury accident and the injury distribution were used to compute a total accident cost for each severity index as shown in Figure 1. This cost-severity index relationship is represented graphically in Figure 2. Table 1 shows some of the roadside hazards and their severity indices. An expected accident cost for each of these objects could be found by using Figure 2 and the assumed severity index. The guide recommends the use of the severity indices developed by Weaver "in the absence of more definitive criteria," alluding to the lack of confidence in these severity indices.

TABLE 1 Examples from the earliest severity index for roadside objects (*7*).

Obstacle	Description	Severity Index
Utility Pole	All	7.1
Rigid Signpost	Single-Pole	4.7
Median Barr.	Concrete	4.2
Guardrail	W-Section	3.7
Trees	All	3.0
Curb	Mountable	2.4

Severity Index	% PDO Accidents	% Injury Accidents	% Fatal Accidents	Total Accident Cost
0	100	0	0	$ 700
1	85	15	0	2,095
2	70	30	0	3,490
3	55	45	0	4,885
4	40	59	1	8,180
5	30	65	5	16,710
6	20	68	12	30,940
7	10	60	30	66,070
8	0	40	60	124,000
9	0	21	79	160,000
10	0	5	95	190,000

FIGURE 1 1977 AASHTO Barrier Guide Severity index definition.

These same recommended severity indices were used in the Benefit/Cost program developed by FHWA in 1985, with some additional indices that account for redirection, penetration, and rollover(*8*). The new severity indices were based on the previously developed scale because there existed a relationship between cost and severity index. McFarland also improved the severity indices used in the 1977 Barrier Guide by using 1978-79 Texas accident data (*9*). He accounted for severity differences of urban and rural collisions. The severity index was assigned to the object based on the cost of the accidents, using the scale developed by Weaver. This is the reverse of the original severity indices in which the objects were assigned a severity index and then the accident costs computed. Although the new severity indices developed are more objectively based, the ranking is based on cost rather than directly on severity.

The ROADSIDE program uses similar severity indices in its benefit/cost analysis (*10*). In general these indices are lower than those used in the 1977 AASHTO Barrier Guide because they account for low-speed impacts. This program also provides different indices for both the face and ends of hazards, if applicable. Again, these indices were developed by expert opinion to fit the severity-cost relationship developed earlier.

Another cost-based type of hazard model is one that equates all injury accidents to an equivalent number of property damage only (PDO) accidents. This conversion from injury accidents to PDO accidents is based on the relative costs of the accidents. Different high accident roadway segments are located and the injury accidents at those locations are then all converted to an equivalent number of PDO accidents. The locations with the highest number of equivalent PDO collisions are selected for redesign. The conversion method developed in Kentucky is as follows (*11*):

$$EPDO = 9.5(F+A) + 3.5(B+C) + PDO$$

where,

- EPDO = Equivalent number of property damage only collisions;
- F+A = Number of fatal and serious injury accidents per year; and
- B+C = Number of minor injury accidents per year, PDO = Number of property damage only collisions.

Both the Tennessee Department of Transportation and Glennon have also developed similar models based on accident costs (*12*) (*13*). Both of these models compute what they call a "severity index," which is a measure of accident frequency and severity combined.

The Tennessee model is:

$$SI = \frac{4F+I}{Total}$$

where,

- SI = Tennessee severity index;
- F = Number of fatal accidents per year;
- I = Number of injury accidents per year; and
- Total = Total number of accidents per year.

The model developed by Glennon is:

$$SI = \frac{25F+6I+PDO}{Total}$$

where,

- SI = Glennon severity index;
- F = Number of fatal accidents per year;
- I = Number of injury accidents per year;
- PDO = Number of property damage only accidents; and
- Total = Total number of accidents per year.

All three models place different emphasis on each type of accident. This is because all the equations are based on supposed accident costs which are highly subjective and variable with time.

This type of model is important because it is currently used by several states. It incorporates the volume and severity of accidents in a single step, so there is really no severity index that can be singled out. This method only

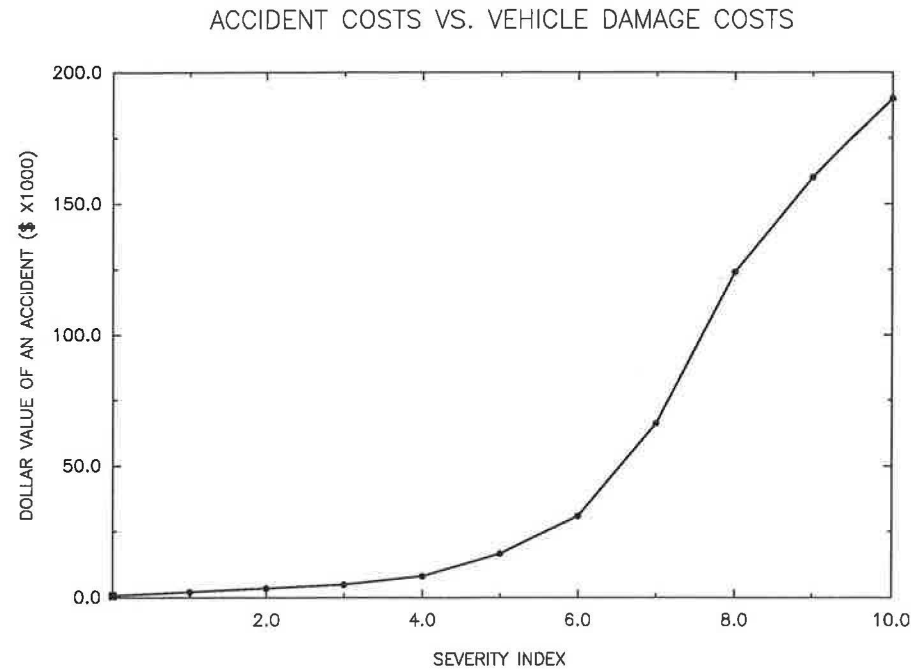

FIGURE 2 1977 AASHTO Barrier Guide Severity index and accident cost.

locates high-accident locations without the ability to determine the specific hazardous characteristics. It can only be used to evaluate accident locations, not predict number and severity of accidents. One purpose of defining a new severity index to be used in a hazard model is to replace this model with one that can be used to predict accidents on new roadways and on rehabilitations rather than only react to hazardous conditions on existing roadsides.

Accident Data Probability Severity Models

The severity indices discussed so far were designed for use in benefit-cost analyses or had meaning only in relation to the severity indices of other objects. Another type of index is one that measures probability of serious injury given that a collision has occurred. A common hazard model that uses this type of severity index was developed by Glennon and is the following (*14*):

$$E(I) = V \quad P(E)\, P(C|E) \quad P(I|C)$$

where,

- E(I) = Expected number of injury accidents per year;
- V = Traffic volume in vehicles per year;
- P(E) = Probability of a vehicle encroachment while traversing length of roadway in which a collision could occur;
- P(C|E) = Probability of a collision given an encroachment has occurred; and
- P(I|C) = Probability of an occupant injury given a collision has occurred.

The first two terms, P(E) and P(C|E), account for the frequency of collisions. The last term, P(I|C), indicates the severity of the collision determined from a severity index or severity model. The P(I|C) represents the probability of a certain injury level given that a collision has occurred.

A severity index that represents the probability of injury is advantageous because it is free from dependence on cost and could ideally be developed using accident data rather than expert opinion. This type of model also has predictive capabilities for comparing design alternatives rather than just being an evaluation tool for existing roadways.

Most of the models that predict probability of injury are found from national or state accident data. If accident data were complete, accurate, and specific, developing these probabilities would be a simple task. Unfortunately, several difficulties are encountered when using accident data.

The first difficulty is in deciding how to measure injury. Two measures are available in the accident data -- the Police Reported Injury Score (PRIS) and the

Abbreviated Injury Score (AIS). The PRIS is the same scale that is used on police reports. The codes and their meanings are shown in Table 2. Each occupant is given a code which indicates the outcome of that occupant's injuries. The AIS is a measure of the severity of injuries. The AIS definitions are shown in Table 3. A score is given to the six worst injuries on each occupant.The AIS is a more reliable measure because the scoring is based on medical data, whereas the PRIS is based on the opinion of the reporting officer. Unfortunately, the PRIS is available in more data than the AIS, therefore it is generally used in developing severity models.

TABLE 2 Definitions of police reported injury scores.

PRIS	Injury Outcome
0	No Injury
C	Possible Injury
B	Nonincapacitating Injury
A	Incapacitating
K	Killed
U	Unknown

TABLE 3 Definitions of abbreviated injury sources.

AIS	Injury Severity
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum (Unsurvivable)
9	Unknown

The second drawback to using accident data is unreported accidents. The unreported accident problem arises when finding the P(I|C) by dividing the number of serious injury collisions by the total number of collisions. It is assumed that most serious injury collisions are reported, but the total number of collisions is uncertain because an unknown number of minor injury and Property Damage Only (PDO) collisions are not reported. A study by Mak and Mason showed that 11.2 percent of utility pole collisions were unreported and 68 percent of small sign support collisions were unreported (*5*). If nearly all utility pole collisions are reported, but only the more serious injury sign support collisions are, then it might appear that a larger percent of collisions with small sign supports result in serious injury. Using accident data that does not account for unreported accidents could potentially result in a higher severity index for a small sign than for a utility pole.

Another drawback of most accident data, lack of specificity, was pointed out by Mak (*16*). Most data -- both state and national -- is not specific enough to compare different objects. For example, in the NASS data definitions of object hit, all guardrail ends are grouped together. When trying to find the severity of end collisions with guardrails, one would be using both blunt end rails and breakaway cable terminals in the same calculations. This lack of detail makes finding the probabilities of injury difficult and sometimes meaningless.

In an exhaustive study of the 1979-1981 Texas accident data, several calculations of the probability of injury for many objects were performed (*16*). Three different measures of injury were investigated:

- Percent fatal and non-fatal injury (% F+I) accidents;
- Percent incapacitating and fatal (% A+K) injury accidents; and
- Percent severe to fatal injury (% AIS 3) accidents.

This study also used national accident data to compare these measures of injury with those developed using the Texas accident data. Although the results were similar, they did not appear reliable because of the unreported accident and specificity problems discussed earlier.

Relative Severity Index

Another type of accident data based severity index is interesting even though it is difficult to use in practice. The relative severity index (RSI) was developed using the logarithm of accident frequencies (*16*). The RSI is calculated as follows:

$$RSI=10*\ln\left(\frac{\%(A+K)_o}{\%(A+K)_a}\right)$$

where,

- ln= Natural logarithm;
- $\%(A+K)_O$= Percent incapacitating (A) and fatal (K) injury accidents for the specific roadside object under consideration; and

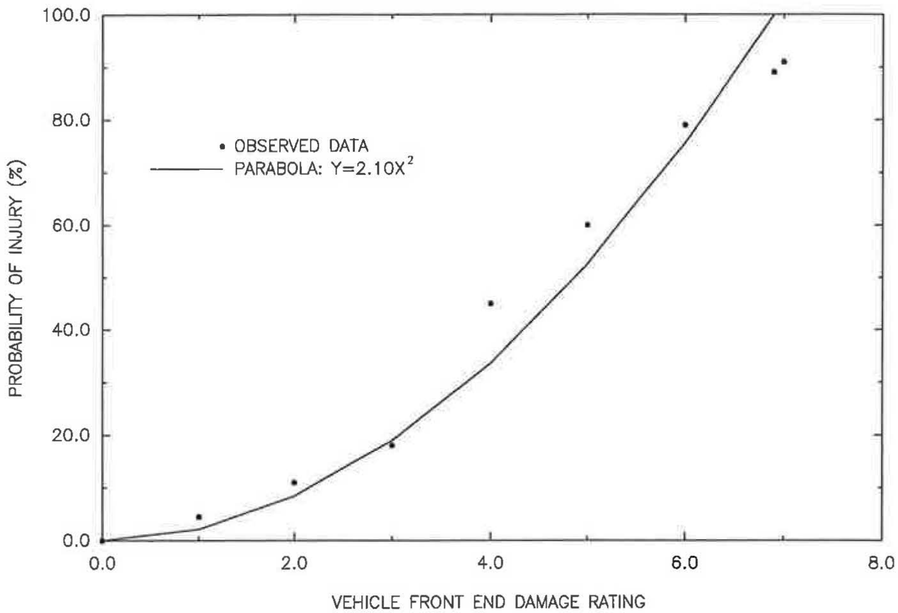

FIGURE 3 Relation between Probability of Injury and Vehicle Front-End Damage.

- $\%(A+K)_a$ = Average percent incapacitating and fatal injury accidents for all roadside objects.

This index is interesting because it results in values that have meaning relative to the average severity of all roadside accidents. The logarithm of the ratio makes the RSI positive if accidents with the object result in A+K injury more often than the average roadside collision. Likewise, the RSI will be negative if collisions with an object are less harmful than the average collision. Several reasons exist for not using this model. First, it is not related to cost so it cannot be used in the hazard models for benefit-cost software that relate the severity index to cost. It also does not fit in the model that uses probability of injury. This model also suffers from the same data problems of unreported accidents and poor specificity.

Crash Test Severity Models

A final type of severity model is one that was developed using crash test results [17]. Generally, these models use both accident data and crash test results. Using observed accident data, a relationship was developed between the vehicle front-end damage rating (TAD) and the probability of injury as follows:

$$P(Injury) = 2.10(TAD)^2$$

Figure 3 shows the data points on which this equation is based. Similarly the following relationship was found between TAD and vehicle resultant accelerations in crash tests:

$$TAD = 0.40\ A_r$$

By substituting the TAD from equation 7 into equation 6, the following relationship was derived:

$$P(Injury) = 0.336 A_r^2$$

Figure 4 shows this relationship graphically. Although the data is too limited to assign any significance to these relationships, the method shows promise for using crash test results to develop severity models.

Another study involving crash tests linked lateral occupant impact velocity and ridedown acceleration in barrier impacts to a severity index using accident reconstruction with the following resultant relationships (*18*):

$$SI = V_{lat}/8$$
$$SI = a/4$$

where,

- SI = Severity Index;
- V = Lateral occupant impact velocity; and
- a = Ridedown acceleration.

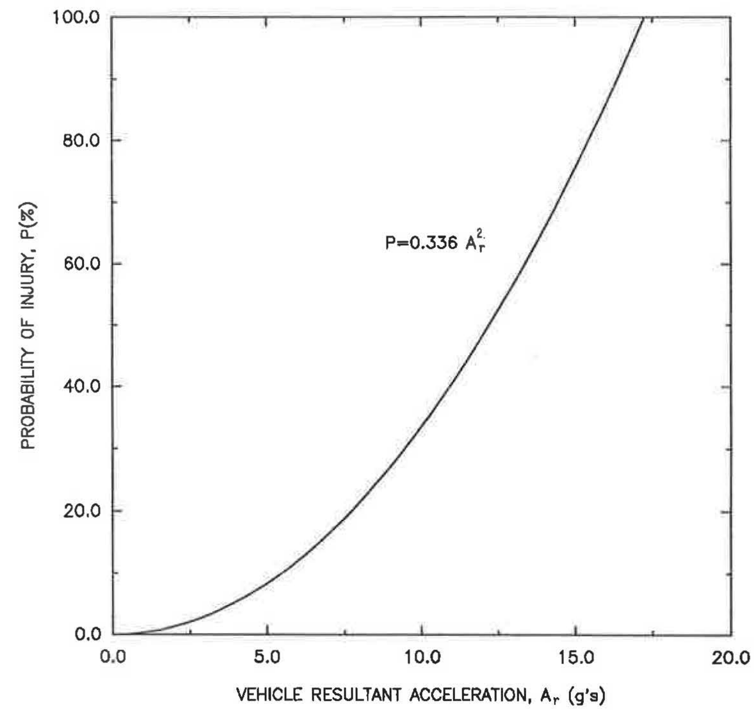

FIGURE 4 Relationship between Probability of Injury and Vehicle Resultant Acceleration.

These relationships then allow crash tests and computer simulation to define a severity index for different barriers at different speeds and impact angles. The severity index developed in this study has a range from 1 to 10. An assumption of the severity model is that a linear relationship exists between the maximum AIS and the severity index. The weakness of the model is that the relationship between V_{lat} and the maximum AIS is based on limited data and further data for other types of objects would be expensive to obtain. The strength of this model is that it varies with impact parameters such as speed and angle. If a roadway designer can estimate the impact speed and angle on a roadway, the severity of collisions with the barriers can be predicted for that particular section of roadway.

Summary of Existing Models

The severity models that currently exist have been based on expert opinion, accident data, crash test results, and computer simulation. Models based on engineering judgements are subjective and generally designed to relate to injury costs which are also subjective. The accident data models established that vehicle and accident characteristics can be used to predict injury severity, but problems of unreported accidents and low level of detail make most of these models unreliable. Crash test results used alone or with computer simulation show promise for developing models usable both for evaluating crash tests and designing roadsides. The weakest part in these models is in linking vehicle or impact measurements with probability of occupant injury. Because of the difficulties with the current severity indices and models, new direction in the development of these indices is needed.

PROPOSED SEVERITY MODELS

General Severity Model

Because of the subjective and varying assignment of costs to injuries, evaluating roadside designs by change in probability of injury rather than benefit/cost ratios is more reliable. Glennon's hazard model, given in equation 4, is an appropriate method of using probabilities of injury for evaluating roadside safety. The severity model should predict P(I|C). Because the probability of injury is generally different in frontal than in side-impact collisions, the severity model should account for both types. In order to account for this difference, the following general severity model will be used:

$$P(I|C)=P(I|S)\ P(S|C) + P(I|F)P(F|C)$$

where,

- $P(I|C)$ = Probability of injury given a collision has occurred;
- $P(I|S)$ = Probability of occupant injury given a side impact;
- $P(S|C)$ = Probability of side impact given a collision has occurred;
- $P(I|F)$ = Probability of occupant injury given that a frontal collision has occurred; and
- $P(F|C)$ = Probability of frontal impact given a collision has occurred.

Because frontal and side collisions account for nearly all the roadside collisions, these are the only two accident scenarios that will be investigated. The following sections will discuss possible methods of determining P(S|C) and P(F|C) and then present four models that may be used for predicting the P(I|F) and P(I|S) terms.

Data Sources

Both crash test results and accident data will be used in the models. Crash test results on most roadside appurtenances are contained in a Federal Highway Administration (FHWA) data base containing 1,942 tests with 80 variables for each test. Information on crash tests can be obtained from this source and the full crash test reports. The accident data bases that will be used are the National Accident Sampling System (NASS) and the special studies of the NASS. The NASS is a statistically based sampling of every type of motor vehicle accident in the United States for a given year. When the NASS accidents are multiplied by a weighting factor, they represent the number of all accidents in the United States in a given year. Several subsets of the NASS, called special studies have been developed. They give more detailed information but are not statistically based samples. The studies considered for use in this research are the Longitudinal Barrier Special Study (LBSS), the Pole Special Studies, and the Crash Cushion Special Study.

The NASS data will be used to find the proportion of frontal and side collisions with different objects, although the probability of frontal or side collisions could be more site specific than national accident data. State accident data could be used to find the impact directions. Another option is for the roadway designer to use encroachment model software that predicts whether the collision will be frontal or side.

Specific Severity Models

The next section will review four possible methods of developing severity models. Because of the availability of the police reported injury score in the data, A+K will be used as the measure of injury.

Accident Data Regression Model

The first two models will use accident data alone. The NASS and the appropriate special studies data base will be used for the first model. A logistic regression model of the following form is proposed:

$$P(A+K|C)=\beta_0+\beta_1 V_{imp}+\beta_2\theta_{imp}+\epsilon$$

where,

- $P(A+K|C)$ = Probability of an A or K Injury, given that a collision has occurred;
- β_0 = Regression Coefficients;
- V_{imp} = Impact Velocity;
- θ_{imp} = Impact Angle; and
- ϵ = Error.

A logistic regression model must be used in this case with a binary dependent variable.

The use of a binary dependent variable in regression analysis means that the data does not have to be a representative sample of the dependent variable. In previous research, a logistic regression model was attempted for the LBSS data, but a binary dependent variable was not used (*16*). The results were not useable because the LBSS is not a representative sample of the accident population. A logistic regression with a binary dependent variable should produce better results since it will not be affected by unreported accidents and nonrepresentative data such as the LBSS. This model would be developed for different objects and different impact directions. A designer would enter estimates for impact velocity and impact angle to find the probability of injury for both frontal and side impacts. The total probability of an A+K injury could then be found using the general severity model in equation 9.

Modified Accident Data Regression Model

The previous model uses independent variables that intuitively seem to be directly related to the injury everity of occupants. The drawback to that model is that it may be difficult for a roadway designer to determine appropriate values for the impact velocity and impact angle. Other variables such as horizontal and vertical curvature, speed limit, and roadway classification can be readily found by a designer. Although these variables appear more appropriate for predicting encroachments, they may be valid predictors of severity as well. The roadway curvature could be an underlying determinant of impact angle. Likewise, the speed limit could be a surrogate measure for impact speed. The following model is thus proposed:

$$P(A+K|C) = \beta_0 + \beta_1 C_h + \beta_2 C_v + \beta_3 P + \beta_4 Cl + \beta_5 SL + \beta_6 SW + \epsilon$$

where,

- $P(A+K|C)$ = Probability of an A or K Injury, given that a collision has occurred;
- β_i = Regression Coefficients;
- C_h = Horizontal Curvature;
- C_v = Vertical Curvature;
- P = Population Density (Urban, Rural);
- Cl = Roadway Classification (Interstate, State, Local);
- SL = Speed Limit;
- SW = Shoulder Width; and
- ϵ = Error.

Again, a logistic regression would be used with a binary dependent variable. NASS, Special Studies, and possibly state accident data could be used to develop this model. This model would be simple for the designer to use and simple to develop for the many objects that are already located on the roadside. A disadvantage of this model is that it could not be used for evaluating crash test results.

Crash Tests and Special Studies Model

In this model the crash test data and the LBSS will be used to predict the Vehicle Damage Index (VDI) based on the impact speed and velocity of the vehicle. The NASS data will be used to determine a relationship between VDI and probability of injury for each impact direction. The difficulty in using crash test data for predicting injury is that there is no direct link between crash test measurements and occupant injury. Because vehicle damage measurements are the only common variable in crash test and accident data, VDI will be used as the link between crash tests and injury.

A regression model of the following form could be calculated using the crash test data and appropriate special studies.

$$VDI = \beta_0 + \beta_1 V_{imp} + \beta_2 \theta_{imp} + \epsilon$$

where,

- VDI = Vehicle Damage Index;
- β_i = Regression Coefficients;
- V_{imp} = Impact Velocity;
- θ_{imp} = Impact Angle; and
- ϵ = Error.

Log-linear and log-log models could also be tried using the same variables. These independent variables were chosen because they could be found or estimated by the roadway designer and because they intuitively appear to affect severity. Models for frontal and side could be developed.

The NASS data would be used to find a relationship between VDI and probability of injury. Because the NASS is representative of all collisions, a graph similar to that shown in Figure 3 could be developed in which the VDI would be used instead of the vehicle front end damage rating. Unreported accidents should not be a problem because most of the unreported accidents are minor injury collisions. These low injury accidents should, in general, have small VDIs. The probability of an A+K injury should go to zero as VDI goes to zero and the lower end of the graph could be extrapolated if this does not occur. The roadside design community has had difficulty finding a relationship between vehicle damage measurements and occupant injury. Although this difficulty may occur in the development of this model, there may be certain types of objects and impact conditions for which this relationship is strong. For example, a study of pole collisions showed that pole size and vehicle crush are good predictors of injury severity in side impacts (*15*). This model could possibly be used only for those objects in which a good relationship can be found.

In this model the roadway designer will again input accident conditions to predict probability of serious severity. As the number of crash tests increases, this model will become more reliable. Most of the crash tests are currently performed at 60 mi/h, but lower speed tests will most likely be performed in the near future. These tests will make the regression equation a better predictor of injury. Likewise, more accident data will strengthen the relationship between VDI and probability of injury.

Crash Test Regression Model

Severity models are valuable not only for the design of roadsides, but also for evaluating crash test results. Because of the variables used, this model is most appropriate for evaluating roadside appurtenances in full-scale crash tests, but it could possible be used for evaluating roadway changes also. This model will be developed completely from crash tests results. It will use measurements taken from anthropometric dummies to relate vehicle impact conditions to probability of injury.

As discussed earlier, there is little evidence to show a correlation between vehicle-based measurements and occupant injury. Some measurements taken from anthropometric dummies -- Head Injury Criteria (HIC) and Thoracic Trauma Index (TTI) -- have, however, been shown to be related to the probability of injury (*19*). In this model crash tests that used dummies and that had TTI and HIC measured could be used to develop regression models to predict TTI and HIC and therefore the probability of injury. The independent variables would all be items that could easily be measured in crash tests without using dummies. Regression models with the following dependent and sample independent variables would be used:

$$TTI \text{ (or HIC)} = \beta_0 + \beta_1 V_{imp} + \beta_2 V_{occ} + \beta_3 C_{area} + \beta_4 a_{rd} + \epsilon$$

where,

- TTI = Thoracic Trauma Index;
- HIC = Head Injury Criteria;
- β_i = Regression Coefficients;
- V_{imp} = The impact velocity of the vehicle;
- V_{occ} = The occupant impact velocity;
- C_{area} = The damaged area of the vehicle;
- a_{rd} = Ridedown acceleration, and
- ϵ = Error.

Currently the roadside design research community does not like to use dummies in full-scale crash tests. Tests with roadside appurtenances are especially severe and can often ruin these expensive dummies. Additionally, sometimes the impacts are so severe that the dummy measurements are difficult to take or interpret. The ultimate objective would be to run enough crash tests with dummies to obtain regression models that relate vehicle-based measurements to probability of injury and thus eliminate the need for anthropometric dummies. New appurtenances could be crash tested and the already-established regression equations could be used to relate the crash test variables to the probability of injury.

This type of model has already been developed for side-impacts with breakaway luminaires (*19*). The regression model to predict TTI is shown above:

$$TTI = \frac{1}{33.33}(0.9021^{r} \cdot 0.9387^{s}) V_i^{2.5} \left(\frac{c_e^{1.25}}{10\sqrt{\dot{c}_i}} \right)$$

where,

- TTI = Thoracic Trauma Index;
- r = The longitudinal distance between the occupant and the impact point in inches;
- s = The actual lateral flail distance between the dummy's head and the interior of the vehicle. This distance is measured at the elevation of the dummy's ear in inches;
- c_e = The maximum external static crush of the vehicle in feet; and
- c_i = The average velocity of the inner door surface into the passenger compartment.

This model has an R^2 of 0.90 and was developed with a limited number of data points within a narrow range of speeds. With more tests at different velocities, even more confidence could be associated with using these regression models to replace anthropometric dummies.

CONCLUSIONS

Severity models have been derived from expert opinion, accident data, crash-test data, and computer simulation. The most promising models for reliable prediction of injury are based on an objective analysis. No widely accepted models currently exist for use by roadway designers. The models developed in this research are designed to be used by designers. Whether the models in this research can be successfully developed or not, the process of developing them will be valuable in itself. This research will be helpful in identifying data needs for both crash tests and accident data. Knowing what variables to measure in crash tests to link them to injury is important. Gaps in the accident data will undoubtedly be identified. This information could lead to better data collection techniques that will supply the information either to successfully develop new severity models or improve existing ones.

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