Methods for Improving Analysis of Roadside Safety

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This paper reviews the state of the art of analysis of roadside-safety improvements. Particular attention is given to the roadside-hazard model developed by Glennon. The need for additional research to validate or add precision to the Glennon model is demonstrated. An empirical accident study is suggested that relates the hazard of specific roadside obstacles to design, operating, and environmental variables. The proposed analysis method assumes a Poisson probability distribution and uses Bayes' theorem for the construction of a discrete model for precisely predicting the hazard of any roadside location.

In the 1960s, highway accidents increased at an alarming rate. By 1972, the annual toll was 56 600 persons killed and more than 2.1 million injured (disabled beyond the day of injury). Of these, 19 900 persons died in single-vehicle accidents (e.g., ran off road, hit fixed object, or overturned)—a significant 34 percent of all highway fatalities (1). In addition, the chance of death is three times greater in single-vehicle accidents than it is in all other highway accidents (2). These human and economic losses can no longer be tolerated. Clearly, positive action is required to change this record of highway death and injury.

Another reason for giving special attention to this kind of accident is that it represents the most visible form of failure in the driver-vehicle-roadway system. Circumstances caused by other drivers and other vehicles are less important in single-vehicle accidents than in multivehicle accidents (2). Therefore, reducing the frequency and severity of single-vehicle accidents by implementing roadway improvements offers one of the most clear-cut opportunities for improving highway safety.

The hazards associated with roadsides are obvious to anyone who drives. Despite attempts to adequately design roadways, there is great danger to a vehicle that leaves the traveled way. Roadside obstacles do not always give the driver who has inadvertently left the pavement a chance to avoid, or at least survive, an accident. The elements of the roadside that contribute heavily to the consequences of single-vehicle accidents are obstacles such as bridge abutments and piers, bridge rails, rigid signposts, rigid luminaire supports, utility poles, trees, drainage structures, steep side slopes, and guardrails.

Quantitatively, the degree of accident hazard associated with a roadside obstacle can be defined in several ways. The accident hazard is a measure of the potential for a particular obstacle to experience a given time rate of accidents that have some average consequence (such as average cost, number of fatalities, or ratio of number of injury-plus-fatal accidents to total number of accidents). At any roadside location, then, the degree of accident hazard is a function of two variables: accident frequency and accident severity. When two locations are compared, if both have the same accident frequency, the location that has the lower accident severity is less hazardous. If both locations have the same accident severity, the location that has the lower accident frequency is less hazardous.

EARLY EVOLUTION OF ROADSIDE-SAFETY IMPROVEMENT

In the past, design efforts to improve roadside safety were limited. Many highway designers felt that a driver who ran off the roadway deserved the consequences of his or her imprudence. As the evidence mounted of the increase in single-vehicle accidents, however, this philosophy gradually changed and the ran-off-road driver became an important consideration in highway design. Consequently, many state highway departments began an active attempt to improve roadside safety.

In an overreaction to the recognition of the need for improved roadside safety, highway guardrails were at first thought to be the panacea. Large quantities of guardrail were placed where none was needed or where a minimum of slope grading could have eliminated the need. The tragic side of what was otherwise a promising improvement in roadside safety was the increase in the frequency of spectacular accidents involving guardrails.

This era of new highway-guardrail installations was marked by a lack of objective criteria for evaluating the consequences of alternative roadside designs. Warrants for guardrail installation were subjectively based on relative judgment. This judgment varied greatly from one state to another, precluding the possibility of minimizing the consequences of running off the roadway.

In 1966, Glennon and Tamburri (3) developed the first, now widely used, objective criteria for guardrail installation. A mathematical model was introduced that compared the relative safety of protective guardrails with various combinations of embankment parameters. The relationship was based on comparative severity indices for samples of ran-off-embankment and guardrail accidents.

Another study in 1966, by Hutchinson and Kennedy (4), was a major breakthrough in terms of understanding and predicting the nature of single-vehicle accidents. This study provided empirical data on the nature of roadside encroachments on freeways and included the following relationships:

1. The frequency of roadside encroachments as a function of traffic volume,
2. The exceedance distribution of encroachment angles, and
3. The exceedance distribution of lateral displacements of encroaching vehicles.

This study led to the eventual adoption of the 9.15-m (30-ft) clear-zone concept because it documented that very few vehicles encroached more than that distance from the edge of the traveled way.

Also during this period, other improvements in roadside design evolved. Embankments and cut slopes were flattened to increase the chance of recovery for errant vehicles. Full-shoulder widths and clear-safety zones were provided along the roadway. Better guardrail and median-barrier designs were developed, innovative breakaway sign and luminaire supports were discovered, and effective impact-attenuation devices were invented.

As a result of this evolution in the technology of roadside-safety design and because of the emphasis created by the AASHO publication, Highway Design and Operational Practices Related to Highway Safety (5), many states began a more comprehensive attack on the roadside-hazard problem. Some states even funded specific programs to reduce roadside hazards on existing highways. These programs all followed the same general strategy, which simply says

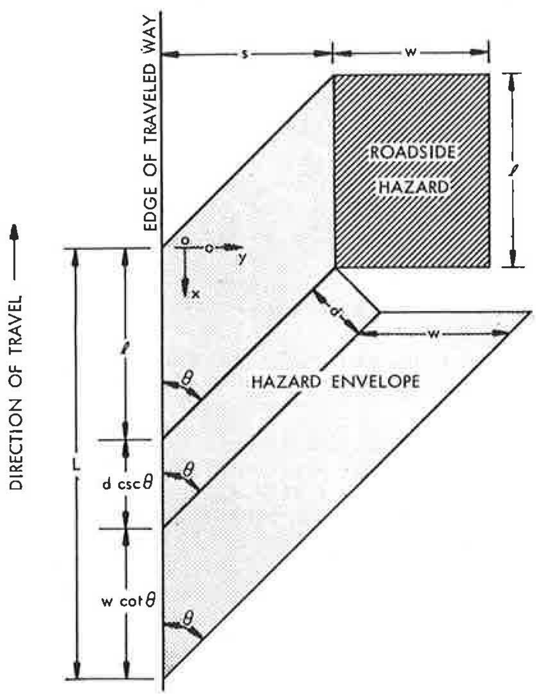
1. Remove unnecessary objects,
2. Move those objects that cannot be removed (this includes moving to a protected location or moving laterally),
3. Reduce the impact severity of those obstacles that cannot be moved (this includes flattening side slopes and installing breakaway devices), and
4. Protect the driver from those obstacles that cannot otherwise be improved by using attenuation or deflection devices.

This approach is ideal if sufficient funds are available to do everything needed. Under ever-present economic constraints, however, trade-offs must be made, even in each of the four basic concepts. The highway administrator is constantly faced with the problem of evaluating many alternatives. Therefore, a definite need exists for methods by which administrators can compare alternative safety improvements and thereby achieve the greatest return within the constraints of available funds.

RECENT ROADSIDE-HAZARD MODELING

The cost-effectiveness model developed by Glennon (6) provides a basic analysis technique for comparison of roadside improvements. This model, in a slightly less objective form, is also given in the AASHTO barrier guide (7).

Figure 1. Schematic illustration of roadside obstacle and its relationship to an encroaching vehicle.



The model depends on the concept that an injury-producing roadside impact is a result of a sequence of four conditional events. First, the vehicle must be within the discrete increment of roadway associated with a potential collision with the roadside obstacle. Then, a roadside encroachment must occur. Next, the lateral displacment of the vehicle must be great enough for collision with the roadside obstacle. And finally, the collision must be of sufficient magnitude to produce an injury.

This sequence of events suggests a conceptual approach for evaluating the degree of hazard for roadside situations. Such an approach considers the vehicular exposure; the expected vehicular-encroachment rate; the expected distribution of encroachment angles; the expected distribution of lateral displacements of encroaching vehicles; and the severity, size, and lateral placement of the roadside obstacle. Figure 1 is a schematic illustration of the increment (L) of highway length associated with a particular roadside obstacle. The hazard envelope is defined by the locus of the right-front corner of the colliding vehicle.

The description of variables suggests that a mathematical relationship is required to truly evaluate the hazard index of a particular roadside situation. For a given angle of encroachment (θ) the explicit hazard equation (6) is as follows:

$$H = (E_f S/5280)\left[l\int_{s}^{\infty} f(y)dy + \int_{l}^{l+d\csc\theta}\int_{s+(x-l)\cos\theta\sin\theta}^{\infty} f(y)dydx + \int_{l+d\csc\theta}^{l+d\csc\theta+w\cot\theta}\int_{s+d\cos\theta+(x-l-d\sec\theta)\tan\theta}^{\infty} f(y)dydx \right] \quad (1)$$

where

- H = hazard index (number of fatal and non-fatal-injury accidents per year),
- E_f = encroachment frequency (number of encroachments per mile per year),
- S = severity index (number of fatal and non-fatal-injury accidents per total number of accidents),
- l = longitudinal length of obstacle (ft),
- w = lateral width of obstacle (ft),
- s = lateral placement of obstacle (ft),
- d = width of vehicle (ft),
- θ = angle of encroachment (°),
- x = longitudinal distance from furthest downstream encroachment point to encroachment point of reference (ft), and
- f(y) = probability density function of lateral displacements of encroaching vehicles.

Each integral expression given in the brackets in the hazard equation multiplied by $E_f/5280$ gives the number of fatal and non-fatal-injury accidents per year expected for each subdivision of the hazard envelope. Thus, the first expression in the brackets represents the contribution of the exposure length l and considers the probability of a vehicle lateral displacement greater than s. The second expression is the contribution of the exposure length d csc θ to the hazard index. The third expression is the contribution of the exposure length w cot θ. The double integrals account for the varying lateral displacements of a vehicle required for collision.

Because of the limitations of the Hutchinson and Kennedy data, the model given by Equation 1 applies only to freeway situations. If a highway department wishes to mount a total roadside-safety program, one in which improvements are implemented in a cost-effective priority order, then the inputs of the model must also account for roadside hazards on highways other than freeways.

More recently, Glennon and Wilton (8) have successfully expanded the applicability of the hazard model. In its final form, the model can be used by a highway department in a cost-effectiveness methodology to (a) determine priorities for implementing roadside safety improvements on all classes of highways and (b) determine priorities for inventorying roadside hazards based on class of highway and average daily traffic. Although this research was limited to developing estimates of the necessary inputs and modifications to the original model, it can be used to predict the effectiveness of roadside-safety improvements on all classes of highways. The new formulation contributes additional information about the nature of vehicle encroachments and the severity indices of roadside hazards for all classes of highways other than freeways—urban arterial streets, rural two-lane highways, and rural multilane highways.

APPLICATIONAL PROBLEMS OF THE ROADSIDE-HAZARD MODEL

Since the publication of the original Glennon model (6), several state highway agencies have attempted to use it. Although the model is conceptually attractive and represents the most advanced analysis technology, and although some states are using some form of the model in their safety programming, other states have been skeptical and have proceeded as usual with some form of administrative wisdom in making decisions on roadside safety. The reasons why some states have rejected the model are as follows:

1. Many practicing highway engineers have not used advanced mathematics since leaving college and are accustomed to analysis and decision-making procedures that use good engineering judgment (whatever that is). Although the Glennon model is a straightforward mathematical formulation, and can also be approximated by a simpler algebraic form that uses probability statements and summations, these engineers have been perplexed by the mathematics.
2. In its most precise form of application, the model is somewhat more complex to use because it requires consideration of contiguous hazards (e.g., a steep embankment immediately behind a breakaway sign support).
3. The application of the model in roadside-safety programming requires a roadside-hazard inventory. Although this has been regarded as a formidable task, the early phases of implementation would require only an inventory of the more severe obstacles on the higher-traffic-volume highways.
4. The model is simplistic because of the nature of available input relationships. For example, the input relationships do not account for variances in the number of fatal and injury accidents based on the dimensions of highway geometric features (such as curvature and grade). Also, although the suggested severity indices vary according to the type of highway (number of lanes, divided or undivided, and urban or rural), they do not directly account for the specific operating speeds (or speed limits) of particular sections of highway. However, this lack of sophistication does not invalidate the model application, although it does make the results less than optimal.
5. Many practicing engineers are skeptical because the model does not demonstrate hazard through direct empirical results.
6. The input relationships developed by Hutchinson and Kennedy (4) and by Glennon and Wilton (8) have not been validated.

Both the Michigan and Maryland Departments of Transportation have sponsored further research in an attempt to improve on the Glennon model. The Michigan study (9) used a multivariate analysis that, with one exception, was unsuccessful in improving the technology but did find that, in general, both the frequency and severity of roadside accidents were higher on highway curves than on tangent sections. The Maryland study (10) generally accounted for the contributions of highway geometrics and operating speeds to roadside hazard, but not in a way that could be incorporated into an objective hazard formulation.

POSSIBLE APPROACHES TO IMPROVING ROADSIDE-SAFETY ANALYSIS

The discussion above illustrates that there are recognized impediments to the application of the Glennon model. To move ahead in the cost-effective implementation of roadside-safety improvements, therefore, will require additional empirical research to either validate and improve the precision of the Glennon formulation or to completely replace it with a more explicit method.

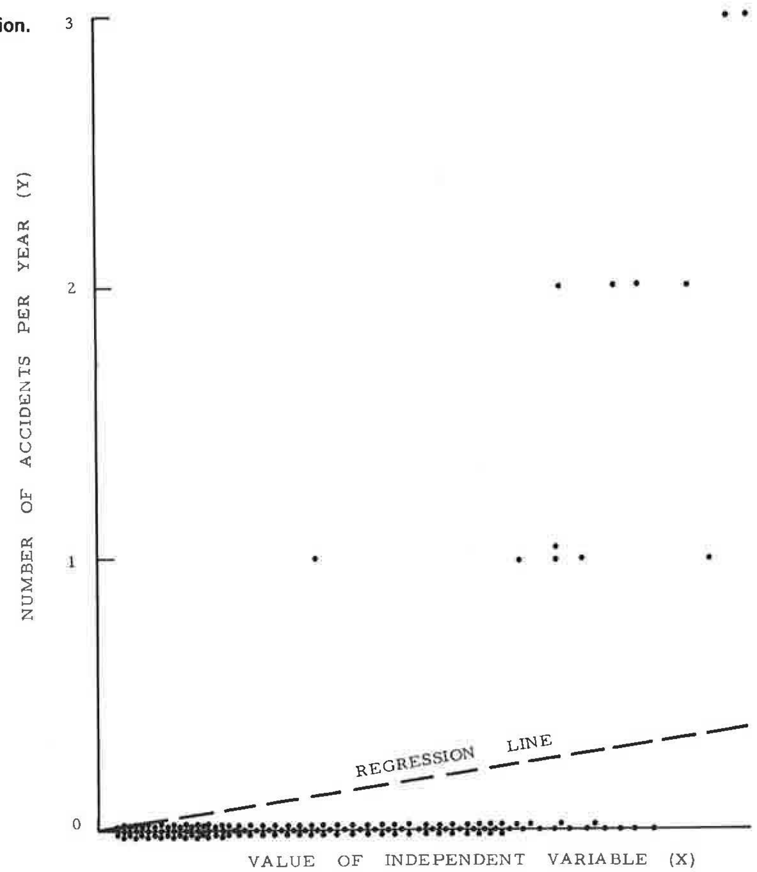
The prediction of the hazard associated with any particular roadside obstacle by using empirical studies is difficult because of both the large number of variables involved and the extremely low probability of a collision with that obstacle. For example, the Glennon model predicts that a concrete bridge column 3.05 m (10 ft) from the edge of the traveled way of a freeway that carries 100 000 vehicles/day will average one fatal or non-fatal-injury accident about every 10 years. Similarly, a rigid light pole 6.1 m (20 ft) from the edge of the traveled way on a freeway that carries 10 000 vehicles/day is expected to average only one fatal or non-fatal-injury accident every 167 years. However, although these probabilities may seem too low to be concerned about, the cost-effectiveness of roadside-safety improvements for the larger, more hazardous obstacles that are placed relatively close to relatively high-volume highways has been clearly demonstrated (6).

Consideration of Standard Multivariate Analysis

Whenever a response variable such as accident rate or number is believed to be a function of several independent variables, the most common study approach is to collect large amounts of data and use a multivariate analysis technique such as multiple regression. A review of several studies in the highway-safety area, however, indicates the futility of these types of studies, even for relatively high-probability situations. And, of course, the indications are that the frequencies of accidents at particular roadside locations are very much smaller than are those for many other situations (such as intersection accidents).

Because roadside accidents are very low-probability events, an attempt to use a standard multiple-regression technique would have problems because of the discrete nature of the dependent variable, i.e., number of accidents per year. This can be illustrated by a simple example, as shown in Figure 2. In this figure, it is assumed that there is one independent variable

Figure 2. Illustrative frequency distribution.



(X) and that the typical 1-year accident response (Y) will be one in which most of the locations sampled have had zero accidents and only a few have had one or more accidents. This type of frequency distribution will produce a regression line such as the one shown. From this simple graphical example, it can be seen that all probability statements about a bad location (one that has a large Y) will be of questionable validity because the actual Y is very remote from the regression line.

Another problem in using regression analysis in this context is that this type of analysis is a continuous representation, whereas many of the candidate independent variables are discrete (e. g., type of roadway, type of object, urban or rural). Thus, the discrete nature of both the dependent and independent variables suggests that another way to model the problem is to create categories for the continuous Xs and build a discrete prediction model rather than a continuous one.

Consideration of Bayes Theorem

The Reverend Thomas Bayes (1702-1761) considered how one might make inferences from observed sample data about the larger groups from which the data were drawn. His motivation was his desire to prove the existence of God by examining the world around him. Mathematicians had previously concentrated on the problem of deducing the consequences of specified hypotheses. Bayes was interested in the inverse problem of drawing conclusions about hypotheses from observations of consequences. He derived a theorem that calculated probabilities of causes based on observed effects.

Bayes' theorem is really nothing more than a statement of conditional probabilities:

$$P(B_r|A) = P(B_r) \times P(A|B_r)/P(A) \quad (2)$$

where

B_i = $B_1, B_2, \ldots B_r, \ldots B_n$ constitute any partition of the sample space,
$P(B_i) \neq 0$ for every i, and
$P(A) \neq 0$.

In other words, the conditional probability of B_r given A is known if all the reverse conditional probabilities and all the unconditional probabilities are known.

This theorem appears to be a more promising approach to the solution of the problem of better predicting the hazard of a roadside obstacle.

Suggested Study of Roadside Hazards

The study suggested here is intended to validate and add precision to the Glennon model for roadside-hazard prediction. It would include an experimental design, a large-scale inventory of roadside obstacles, collection of accident records to match the obstacle inventory, and an analysis that used Bayes' theorem. (Rather than a full-scale study, an alternative plan might be to conduct a pilot study for one kind of roadway or one kind of roadside obstacle. The remainder of this discussion, however, assumes a full-scale study.)

To be statistically tractable, the roadside inventory would require a fairly massive effort. This effort might be facilitated, however, by using the fixed-object inventory recently (1974) mandated by the U.S. Department of Transportation or state photologging records. It would also be necessary to ensure that the candidate independent variables included samples across their entire dimensional ranges. The candidate independent variables are listed below.

General Highway Variables	Design Feature Variables	Roadside Obstacle Variables
Traffic volume	Number of Lanes	Type of obstacle
Environment (urban or rural)	Median width	Lateral placement of obstacle
Type of access control (full, partial, or none)	Shoulder width	Side of placement (median or right side)
Divided or undivided	Degree of curvature	Length of obstacle
	Percentage grade	Width of obstacle
	Presence of curbs	
	Special design features (intersections, gores, and such)	

Accident data could be gathered from statewide computer files. This compilation should be limited to a 1- to 3-year sample to avoid errors caused by highway-design changes. Single-vehicle injury (fatal plus nonfatal) accident records would be matched to inventory records by milepost location and type of obstacle. Although these kinds of accident studies have been known to be unreliable, the major source of error, accident-reporting level, is not a particular problem here because only the more severe accidents (which have higher reporting reliability) are of interest.

In the application of Bayes' theorem to the analysis of the study data, each roadside location is considered to belong to one of two accident classes: good ($Y = 0$) or bad ($Y > 0$). Although there are no formal reasons to not consider all integer values of Y, the number of locations that would have more than one accident is expected to be so small that the estimates would be unreliable.

To see how Bayes' theorem fits the problem at hand, assume temporarily that only one independent variable—X, which has categories $j = 1, 2, \ldots, k$—is necessary to predict the number of accidents. The required estimate is the probability that a location will have one or more accidents in the specified time period given $X = j$. According to Bayes' theorem, this probability is

$$P(Y>0|X=j) = P(Y>0) \times P(X=j|Y>0)/P(X=j) \quad (3)$$

A similar expression exists for $P(Y=0|X=j)$.

Once the categories for an independent variable are selected, it is easy to estimate $P(Y>0|X=j)$ for that variable. The probability, $P(X=j|Y>0)$, is the fraction of locations that are in category j out of the bad-location ($Y > 0$) class. The unconditional probability, $P(Y > 0)$, is simply the fraction of total locations in the bad-accident class. And the unconditional probability, $P(X=j)$, is simply the fraction of total locations exhibiting $X = j$.

The next step in the development of the prediction model is to provide for estimating the probability of more than zero accidents given the set of independent-variable values for each roadside location. This is accomplished by assuming independence of the X_is. For example, for three independent variables,

$$P(X_1=2, X_2=1, X_3=4|Y>0) = P(X_1=2|Y>0) \times P(X_2=1|Y>0) \times P(X_3=4|Y>0) \quad (4)$$

Of course, it would be ideal to avoid the assumption of independence, but to do so would require an analytical description of all the dependencies among the Xs. This is certainly not available from anything less than a very large data set, if it is available at all. Although the independence assumption is exactly equivalent to the additivity assumption used in standard multiple-regression analyses, rather than trying to account for these dependencies, this study could select the variables in such a way as to avoid any logical dependencies. Given the independence assumption then, the model would take the general form,

$$P(Y>0|X_1=j, \ldots X_n=k) = P(Y>0) \times P(X_1=j, \ldots X_n=k|Y>0) \div P(X_i=j, \ldots X_n=k) \quad (5)$$

This model, which simply estimates whether a roadside location is in the bad population, can be transformed into a more explicit model that estimates the unexpected number of accidents by using the assumption that accidents follow a Poisson distribution. By using the previously derived relationships in the Poisson equation, one obtains the following derivation of the expected number of fatal-plus-nonfatal accidents (λ):

$$P(Y=0|X_1=j, \ldots X_n=k) = e^{-\lambda}(\lambda)/0! = e^{-\lambda}$$

$$1 - P(Y>0|X_1=j, \ldots X_n=k) = e^{-\lambda}$$

$$\lambda = -\ln\{1 - [P(Y>0) \times P(X_1=j, \ldots X_n=k|Y>0)/P(X_1=j, \ldots X_n=k)]\} \quad (6)$$

Conceptually, then, this model gives a value equivalent to that of the Glennon model. To validate the Glennon model (or conversely to validate this model by using the Glennon model) requires that the new model be estimated by using only those variables expressed in the Glennon model or its available inputs (e.g., type of highway, average daily traffic, type of obstacle, length of obstacle, width of obstacle, and lateral placement of obstacle). If a reasonable level of correspondence is found, then the more explicit form of the new model can be judged to be the best available representation of roadside hazard.

CONCLUSION

The proposed Bayesian approach to the analysis of roadside hazard merits further investigation. It offers a potential model that could be directly supported by empirical data, rather than a nonvalidated conceptual model of how component events of a roadside accident are conditionally related. It also has the potential for a more precise formulation because the developmental data collection could also consider the relationships of roadside accidents to geometric and traffic-operating variables.

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Procedure for the Evaluation of Completed Highway-Safety Projects

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The highway-safety engineer must constantly make crucial decisions involving the selection and implementation of safety-improvement countermeasures. To facilitate decisions regarding the continuation, addition to, or deletion of various types of highway-safety programs, valid effectiveness evaluations of completed safety projects should be conducted and made available to other engineers. Critical to the decision-making process are quantitative answers as to whether or not the project is accomplishing its intended purposes, how the purposes are being accomplished, and whether the project is producing unexpected or contrary results. Without the evaluation of individual projects, the effectiveness of highway-safety programs cannot be determined and limited safety funds cannot be allocated to those programs that are most effective in saving lives and reducing injuries and property damage. Too often, effectiveness-evaluation efforts are deemphasized because of monetary and staff constraints and the absence of a single, comprehensive procedure, designed specifically for the evaluation of deployed highway-safety countermeasures. In this study, the literature and current practices relative to effectiveness evaluations were examined to determine whether or not existing techniques and methods are appropriate for use in a single methodology for the evaluation of various roadway- or roadside-improvement projects. It was concluded that existing techniques are appropriate but that they should be organized into a structured procedure that would be practical for use by engineers and highway-safety personnel. This paper describes the procedure developed from state-of-the-art techniques for performing effectiveness evaluations of various types of completed highway-safety projects.

National highway-accident statistics (1) indicate that the annual number and rate of traffic-accident deaths have declined to their lowest levels since the early 1960s. This, together with the fact that annual vehicle kilometers of travel have generally increased throughout the same period, indicates that positive gains are being achieved from recent highway-safety efforts. In general, programs aimed at improving highway conditions, vehicle designs and driver awareness are responsible for the improvement in highway safety.

Transportation programs administered by the Federal Highway Administration (FHWA) are directed toward reducing traffic-accident fatalities, injuries, and property damages attributable to highway-system failures (as opposed to vehicle or driver failures). To create a hazard-free highway system, FHWA has developed a collection of highway-safety programs that consists of a full range of projects and types of improvements. These projects include improvements at railroad-highway crossings, installation of pavement markings, improvements at high-hazard locations, and elimination of roadside obstacles. On an aggregate basis, these projects have definitely affected the number and severity of traffic accidents. However, the extent to which individual projects and types of improvements have affected the accident experience at specific locations is not fully known. Thus, the effectiveness of individual projects and improvements needs to be determined. This could be accomplished by conducting effectiveness evaluations of existing highway-safety treatments.

The need to conduct effectiveness evaluations is generally recognized by the highway-safety profession. In fact, evaluation data on project effectiveness is required for all federal-aid safety projects. All too often, however, effectiveness-evaluation efforts are deemphasized because of monetary and staff constraints and the absence of a single, comprehensive procedure capable of evaluating the full range of possible highway-safety treatments.

This paper describes a procedure that was developed specifically for evaluating highway-safety projects. It is based on existing state-of-the-art techniques and procedures and is intended for use by practicing state and local highway-safety engineers for conducting intensive effectiveness-evaluation studies of completed highway-safety projects. The development of the procedure included the development of a guide (2) and a 3-day training session and workshop for practicing highway-safety engineers.

EVALUATION PROCEDURE

A highway-safety project, in the context of the evaluation procedure, is defined as a roadway- or roadside-safety improvement that has been implemented to affect the frequency, rate, or severity (or a combination thereof) of traffic accidents. For a project to be considered a safety improvement, traffic-accident reduction must be its primary raison d'être, although the improvement of traffic operations is allowable as a secondary effect. A project can be composed of one or more countermeasures, implemented at an intersection or on an extended roadway section. A project can also consist of several locations, each of which are treated