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# Development of Roadside Safety Data Collection Plan

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

## FOREWORD

This report presents the results of a study aimed at identifying critical gaps in the state of the knowledge needed to improve roadside safety cost-effectiveness analyses. The product of this study is five proposed research study plans that address the issues identified.

This study is in support of current Federal Highway Administration (FHWA) research efforts to develop an Interactive Highway Safety Design Model (IHSDM). The IHSDM, now in early stage of development, is intended to assist designers in estimating the geometric and roadside safety consequences of design decisions. For the purpose of this study, the procedure now under development under NCHRP Project 22-9, "Improved Procedures for Cost - Effectiveness Analysis of Roadside Features" was assumed to be the roadside safety module of the IHSDM.

Copies of Report FHWA-RD-92-113 are being distributed to the roadside safety research community. A limited number of copies are available from the FHWA R&D Publications and Reports Center, HRD-11. Additional copies are available to the public from the National Technical Information Service (NTIS), Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. A small charge will be imposed for each copy.

Lyle Saxton
Director, Office of Safety and Traffic
Operations Research and Development

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16. Abstract

The purpose of this study is to support the roadside aspect of the FHWA High Priority National Research Area on "Highway Safety Design Practices and Criteria." The objectives of this study are to: (1) identify issues and gaps in the state of the knowledge needed t improve the cost-effectiveness analysis procedure to be developed under NCHRP Project 22-9, "Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features," and (2) develop data collection plans for those issues and gaps that can be addressed with accident data. A conceptual framework of the cost-effectiveness model was first formulated. A list of research topics that could potentially improve the cost-effectiveness model was identified. Five proposed research studies were developed from the list: (1) Validation of Encroachment Frequency/Rate, (2) Determination of Encroachment Frequency/Rate Adjustment Factors, (3) Effect of Roadside Conditions on Impact Probability and Severity, (4) Distributions of Impact Conditions, and (5) Relationships of Impact Conditions, Performance Limits, and Injury Probability and Severity. Detailed data collection plans were developed for each of the five proposed studies. A 1-day meeting of an expert panel was convened to critically review these data collection plans. Also, a data collection plan for a combined proposed studies 1 and 2 was developed.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | ml |
| gal | gallons | 3.785 | liters | l |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| NOTE: Volumes greater than 1000 l shall be shown in $m^3$. | | | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 or (F-32)/1.8 | Celcius temperature | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | l |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| psi | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | ac |
| ha | hectares | 2.47 | acres | $mi^2$ |
| $km^2$ | square kilometers | 0.386 | square miles | |
| | | **VOLUME** | | |
| ml | milliliters | 0.034 | fluid ounces | fl oz |
| l | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.71 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg | megagrams | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celcius temperature | 1.8C + 32 | Fahrenheit temperature | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | psi |

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

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# I. INTRODUCTION

## BACKGROUND

One of the High Priority National Program Areas (HPNPA) for the Federal Highway Administration (FHWA) is "Highway Safety Design Practices and Criteria." The objective of this FHWA HPNPA is "to develop an integrated design process that systematically considers both the roadway and roadside in the development of cost-effective highway design alternatives" through a 10-year or less research program. This particular study focuses on the roadside aspects of this HPNPA objective.

An improved computerized cost-effectiveness model is to be developed under National Cooperative Highway Research Program (NCHRP) Project 22-9, "Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features." The objectives of this ongoing NCHRP study are to develop state-of-the-art microcomputer-based cost-effectiveness analysis procedures for use in:

1. Assessing alternative roadside safety treatments.

2. Developing warrants and guidelines, including those that consider performance levels of safety features.

This improved cost-effectiveness analysis procedure will provide highway agencies with a tool to evaluate roadside safety design and treatment alternatives, replacing existing cost-effectiveness analysis procedure currently in use by the highway agencies, such as the Benefit-Cost Analysis Program (BCAP) used to develop the 1989 American Association of State Highway and Transportation Officials (AASHTO) *Guide Specifications for Bridge Railings*, the ROADSIDE program mentioned in the 1988 AASHTO *Roadside Design Guide*, and the procedure outlined in the 1977 AASHTO *Guide for Selecting, Locating, and Designing Traffic Barriers*.[1,2,3] It is perceived by the FHWA that this improved procedure could become a major component in the integrated design process as delineated in the FHWA HPNPA mentioned above.

This improved cost-effectiveness analysis procedure to be developed under NCHRP Project 22-9 will be based on existing data and information with no provisions for additional research. It is recognized that there are issues and gaps in the state of the knowledge concerning the cost-effectiveness analysis procedure that can be improved upon through additional research efforts. The purpose of this study is to identify these issues and gaps in the state of the knowledge needed to improve the cost-effectiveness analysis procedure and to develop data collection plans for those issues and gaps that can be addressed with accident data. The data collection plans developed in this study can then serve as inputs to the FHWA in its effort to formulate future research program(s) and project(s) to meet the objectives of the HPNPA.

## STUDY OBJECTIVES

The objectives of this study are, therefore, to:

1. Identify issues and gaps in the state of the knowledge needed to improve the cost-effectiveness analysis procedure to be developed under NCHRP Project 22-9.

2. Develop data collection plans for those issues and gaps in the state of the knowledge that can be addressed with accident data.

## SCOPE OF STUDY

The study effort was divided into four major tasks, as follows:

1. Identification of research topics.

2. FHWA review of proposed research topics.

3. Development of detailed data collection plans.

4. Expert panel review of proposed data collection plans.

Brief descriptions of these tasks are presented in chapter II of this report. Chapter III outlines the key components of the planned cost-effectiveness analysis procedures. The study findings and conclusions are summarized in chapter IV. The selected research topics and the associated data collection plans are presented in appendixes A through F. A summary of comments received from the expert panel and the FHWA, and responses to these comments are presented in appendix G.

## II. STUDY APPROACH

As mentioned under "Scope of Study," there are four major tasks to this study effort:

1. Identification of research topics.
2. Panel review of proposed research topics.
3. Development of detailed data collection plans.
4. Expert panel review of proposed data collection plans.

Brief descriptions on each of these four major tasks are presented as follows.

### TASK 1. IDENTIFICATION OF RESEARCH TOPICS

In order to identify the issues and gaps in the state of the knowledge regarding the roadside safety cost-effectiveness model, it is necessary to first know what the key components of the model are and how the components would work together. Ideally, the cost-effectiveness model should first be developed under NCHRP Project 22-9 and the issues and gaps in the state of the knowledge regarding the model will then be identified in this study. However, since NCHRP Project 22-9 is still ongoing and the cost-effectiveness model is not yet developed, it is necessary to first formulate the model structure and its key components or modules conceptually. An outline of the cost-effectiveness model was developed and presented in chapter III of this study.

Based on this conceptual framework of the cost-effectiveness model, a list of issues and gaps in the state of the knowledge that could potentially improve the model was identified by the project staff. The list was then narrowed down to potential research topics by first selecting only those issues and gaps that were considered to be the most critical and could be addressed with accident data. Also, careful consideration was given to selecting topics that have a good probability of success and can be accomplished within the 10-year time frame. This list of potential topics is by no means exhaustive. However, in the opinion of the project staff, these topics represent the most critical issues and gaps in the state of the knowledge. In fact, it is felt that these topics are worthwhile research projects regardless of the development or implementation of the cost-effectiveness model.

A literature search of various data bases, such as the Transportation Research Information System (TRIS), was then conducted to identify relevant literature pertaining to these potential research topics. The relevant literature was then critically reviewed for use with formulating the problem statements and the research approaches.

An interim report was prepared and submitted to the FHWA, summarizing the gaps identified in the state of the knowledge related to the computerized cost-effectiveness model to be developed under NCHRP Project 22-9.[4] Seven potential research topics that can be addressed with accident data were identified. For each potential research topic, a detailed discussion on the study background, objectives, and anticipated results was presented as well as a brief outline of the proposed research approach. These seven potential research topics are as follows:

| Topic | Description |
|---|---|
| 1 | Validation of Encroachment Frequency/Rate. |
| 2 | Determination of Adjustment Factors. |
| 3 | Descriptive Statistics on Vehicle Trajectory. |
| 4 | Effect of Roadside Conditions on Impact Probability and Severity. |
| 5 | Extent of Unreported Accidents. |
| 6 | Distribution of Impact Conditions. |
| 7 | Relationships of Impact Conditions to Performance Limits and Impact Severity. |

## TASK 2. FHWA REVIEW OF PROPOSED RESEARCH TOPICS

These seven research topics were presented to the FHWA in an interim briefing held on November 5, 1991 at the Turner-Fairbank Highway Research Center in McLean, Virginia. The meeting attendees were provided with the interim report prior to the briefing. A brief presentation on the study background and objectives and the seven proposed research topics was first presented by the project staff, followed by open discussions.

There was general agreement among the meeting attendees that these research topics were appropriate and approval was received to proceed with developing the detailed data collection plans for these research topics. Based on comments received during the meeting, some minor changes were made to the research topics. Two of the research topics were combined with other research topics with similar approaches. Research topic 5 on the extent of unreported accidents was incorporated into research topic 1 on validation of encroachment frequency/rate. Research topic 3 on vehicle trajectory was incorporated into research topic 6 on distributions of impact conditions. Also, research topic 4 on the effects of roadside conditions on impact probability and severity was extensively modified in both the objectives and the scope of work. The five proposed research studies selected for further development are as follows:

| Proposed Study | Description |
|---|---|
| 1 | Validation of Encroachment Frequency/Rate. |
| 2 | Determination of Encroachment Frequency/Rate Adjustment Factors. |
| 3 | Effect of Roadside Conditions on Impact Probability and Severity. |
| 4 | Distributions of Impact Conditions. |
| 5 | Relationships of Impact Conditions, Performance Limits, and Injury Probability and Severity. |

## TASK 3. DEVELOPMENT OF DETAILED DATA COLLECTION PLANS

For each of the five proposed studies, a detailed data collection plan was developed, including discussions on the background, study objectives, research approach, anticipated results, and estimated cost and time. The research approach covers such topics as data requirements, sampling scheme, data collection protocol, and analytical procedures.

A second interim report was prepared and submitted to the FHWA, summarizing the detailed data collection plans for these five proposed studies.[5] The detailed data collection plans for the five proposed research studies are presented in appendixes A through E.

## TASK 4. EXPERT PANEL REVIEW

A panel of six experts was formed to provide an independent and critical review of the data collection plans of the proposed research studies. The expert panel members were selected in consultation with the FHWA on the basis of their expertise in roadside safety and their knowledge in the various aspects of conducting research studies with accident data. The six expert panel members are as follows:

Ms. Julie Cirillo, Scientex Corp.
Mr. Forrest Council, Highway Safety Research Center
Mr. Mark Marek, Texas Department of Transportation

Dr. Shaw-Pin Miaou, Oak Ridge National Laboratory
Mr. Frank Richardson, National Highway Traffic Safety Administration
Mr. Charles Zegeer, Highway Safety Research Center

A 1-day meeting of the expert panel members and interested FHWA personnel was convened on April 29, 1922 at the Turner-Fairbank Highway Research Center in McLean, Virginia. The expert panel members and FHWA personnel were provided with copies of the second interim report which details the data collection plans for the selected research topics, prior to the meeting. Brief summaries of the study background, objectives, and scope of work and outlines of the data collection plans for the five proposed studies were first presented at the beginning of the meeting. Open discussions among the expert panel members, FHWA personnel, and the project staff then ensued following the brief presentations.

A summary of the comments from the expert panel meeting and subsequent comments provided by the FHWA are presented in appendix G of the report. Also included in the appendix are responses to the comments by the project staff. The substance of the comments and suggestions was then incorporated into the data collection plans as presented in this report.

## III. ROADSIDE SAFETY COST-EFFECTIVENESS MODEL

As mentioned previously, a conceptual framework of the cost-effectiveness model to be developed under NCHRP Project 22-9 was formulated in the effort to identify the issues and gaps in the state of the knowledge regarding the model. Brief descriptions of the cost-effectiveness model are presented in this chapter for information purposes.

It is envisioned that the cost-effectiveness model to be developed under NCHRP Project 22-9 will be based on encroachment probability and benefit/cost analysis, similar to the existing cost-effectiveness procedures. The basic formulation of the encroachment model is expressed by the following equation:

$$E(C) = \sum_{i=1}^{n} P(E)*P(A|E)*P(I_i|A)*C(I_i) \qquad (1)$$

where $E(C)$ = Expected accident cost
$P(E)$ = Probability of an encroachment
$P(A|E)$ = Probability of an accident given an encroachment
$P(I_i|A)$ = Probability of injury, i, given an accident
$C(I_i)$ = Cost associated with injury i

There are three major components to this cost-effectiveness procedures:

1. An algorithm to predict the frequency of accidents.

2. An algorithm to predict the severity of accidents.

3. A procedure to estimate accident costs and determine benefit/cost ratio.

Brief descriptions of each of these components are presented as follows.

### ACCIDENT FREQUENCY PREDICTION

The accident frequency prediction algorithm is based on the probability of an encroachment, P(E), and the probability of an accident given an encroachment, P(A|E). The basic premise of the encroachment probability model is that the number and severity of roadside accidents occurring at a given site can be related to the number and characteristics of encroachments, i.e., vehicles that inadvertently leave the roadway, at that site. Thus, the model starts with a base or average encroachment rates, e.g., 0.000006 encroachments per million vehicle miles of travel, that is appropriate for the specific highway type. In other words, each highway type may have a different base encroachment rate.

The base encroachment rate is then adjusted for specific site conditions, such as geometric and roadway cross-sectional characteristics. The rationale for these adjustment factors is that encroachments are affected by certain geometric and roadway cross-sectional characteristics and the base encroachment rates should be adjusted to account for these characteristics. For example, previous studies have found that vehicle encroachments are more likely on the outside of curves and the encroachment rate should thus be increased to account for the presence and the degree of curvature of the horizontal curve.

The encroachments are associated with certain characteristics, such as speed and angle of encroachment, and the extent of lateral encroachment. Each of these encroachment characteristics are expressed in terms of probability distributions so that the probability for errant vehicles to have certain combination of encroachment characteristics can be determined from these distributions.

The encroachment characteristics, after modification by the trajectory of the vehicle subsequent to leaving the roadway, determine the probability and impact conditions of an errant vehicle impacting with a roadside object or feature. The trajectory of the vehicle refers to the path of the vehicle and driver inputs, such as braking and steering. The vehicle trajectory is also affected by roadside conditions, such as presence/absence of shoulder, shoulder width, roadside slope, lateral offset of roadside object or feature, etc.

The probability of an accident given an encroachment is estimated using an impact envelope, which is defined as the region along the roadway within which a vehicle leaving the travelway at a prescribed angle will impact the roadside object or feature. The impact envelope is a function of the encroachment angle and the physical dimensions and lateral offset of the roadside object or feature impacted. Another factor influencing the probability of an impact is the encroachment speed and the vehicle trajectory. Some vehicles may stop or recover and return to the roadway prior to impact with the roadside object or feature.

## ACCIDENT SEVERITY PREDICTION

The severity of an accident is a function of many factors, including impact conditions (i.e., impact speed, angle, and vehicle orientation), the size and weight of the impacting vehicle, and the nature of the impacted roadside object or feature. For a given roadside object or feature and impacting vehicle, the conditions under which the vehicle impacts the roadside object or feature, i.e., speed, angle and vehicle orientation, determine the outcome and severity of the accident. When the performance limit of the roadside object or feature is exceeded, e.g., loading is greater than barrier capacity, some catastrophic outcome could occur, such as penetration of the barrier or rolling over the barrier. Under such circumstances, the severity of the impact is usually a function of the catastrophic outcome. For situations where the performance limit is not exceeded, e.g., redirection for a barrier, severity is a function of the impact conditions.

Accident severity is typically expressed in terms of a severity index, which is a surrogate measure for injury probability and severity. Currently available severity indices are developed from various sources, including accident data, simulation and full-scale test results, and to a large degree, subjective judgment.

## COST ESTIMATION AND BENEFIT/COST RATIO DETERMINATION

The accident severity, expressed in terms of a severity index rating, is then converted to societal or accident costs based on some pre-selected cost figures. Most States currently use cost figures developed by the National Safety Council (NSC). The NSC cost figures include estimates of direct costs, such as wage loss, medical expense, insurance administration, legal/litigation cost, and property damage, but do not account for indirect costs, such as the consideration of a person's natural desire to live longer or protect the quality of one's life. The FHWA has adopted the comprehensive cost figures, which are based on the concept of willingness to pay and include the indirect costs mentioned above, and are substantially higher than those of the NSC.[6] The NSC has endorsed the use of the comprehensive cost figures for benefit-cost analyses.[7] In addition, the National Highway Traffic Safety Administration (NHTSA) has also endorsed the use of comprehensive cost figures in benefit-cost analyses.[8]

The accident costs are then combined with direct costs and traffic delay costs to determine total accident costs. When evaluating different safety alternatives, the differences in accident costs between the safety alternatives are then compared to the differences in costs associated with the safety alternatives, i.e., installation and maintenance costs, to determine the benefit/cost ratios. Choice among the safety alternatives can then be made on the basis of incremental benefit/cost ratios, expressed as follows:

$$\text{B/C Ratio}_{2\text{-}1} = (B_2 - B_1)/(C_2 - C_1) \qquad (2)$$

where B/C $\text{Ratio}_{2\text{-}1}$ = Incremental benefit/cost ratio between alternatives 1 and 2
$B_1, B_2$ = Benefits associated with alternatives 1 and 2
$C_1, C_2$ = Costs associated with alternatives 1 and 2

## IV. SUMMARY OF FINDINGS

Based on a conceptual framework of the cost-effectiveness model to be developed under the ongoing NCHRP Project 22-9, issues and gaps in the state of the knowledge that could potentially improve the model and addressed by accident data were identified. Upon review and approval by the FHWA, detailed data collection plans were developed for the following five proposed research studies:

| Proposed Study | Description |
|---|---|
| 1 | Validation of Encroachment Frequency/Rate. |
| 2 | Determination of Encroachment Frequency/Rate Adjustment Factors. |
| 3 | Effect of Roadside Conditions on Impact Probability and Severity. |
| 4 | Distributions of Impact Conditions. |
| 5 | Relationships of Impact Conditions, Performance Limits, and Injury Probability and Severity. |

A 1-day meeting of a panel of experts was convened to critically review and comment on the proposed data collection plans. Also, comments were received from FHWA subsequent to the expert panel meeting. The substance of these comments was incorporated into revising the data collection plans as presented in this report.

## APPENDIX A. VALIDATION OF ENCROACHMENT FREQUENCY/RATE

### BACKGROUND

The basic underlying assumption of an encroachment probability based cost-effectiveness model is that the rate of roadside accidents is directly related to the encroachment rate. The model starts with an average or base encroachment rate and proceeds from there. Needless to say, the encroachment rate is crucial to the validity and accuracy of the cost-effectiveness model. Available data on encroachment rates are limited to three previous studies by Kennedy and Hutchinson, Cooper, and Calcote.[9,10,11]

The approach employed by Hutchinson and Kennedy and Cooper in their efforts to collect encroachment data involved periodic observations of tire tracks along the roadside and/or median areas of highways.[9,10] Much of the data from the Hutchinson and Kennedy study were collected during winter months on snow-covered medians of rural divided highways with speed limits of 70 mi/h (112.7 km/h). Cooper collected the encroachment data during summer months along the roadsides of both divided and undivided highways in Canada. Most of these highways had speed limits in the 50- to 60-mi/h (80.5- to 96.6-km/h) range.

A major limitation of this approach is that controlled encroachments, wherein the drivers intentionally leave the traveled portion of the roadway for whatever reason, cannot be distinguished from uncontrolled encroachments. For example, portions of the tire tracks observed by Hutchinson and Kennedy appeared to be the result of vehicles making U-turns in the median areas. Further, many highways included in Cooper's study had significant volumes of slow-moving, oversized farm equipment that were commonly driven off of the roadway to allow traffic to pass. Since the researchers had no objective criteria for distinguishing controlled encroachments from uncontrolled encroachments, all tire tracks were included in the data, based on which gross encroachment rates were reported.

Another problem with the encroachment data from observation of tire tracks is that most of the studied highways have paved or gravel shoulders. Vehicles encroaching only a short distance from the travelway, i.e, within the shoulder area, would not leave any evidence of an encroachment and thus could not be identified. On the other hand, the presence of paved shoulders reduces the likelihood that tire tracks observed beyond the shoulder areas are from controlled encroachments since controlled encroachments are more likely to occur on the shoulder areas.

Existing encroachment data from observation of tire tracks are also biased by the effects of seasonal and weather changes on the encroachment rates. Much of the data studied by Hutchinson and Kennedy were collected during winter months in Illinois where snowy and icy weather and surface conditions could significantly increase encroachment rates. Conversely, Cooper's data were collected only during the summer months when favorable weather conditions may produce encroachment rates that are lower than the annualized averages.

Figure 1 shows plots of encroachment frequency (encroachments per mile per year) as a function of traffic volume from the two studies. Encroachment rates (encroachments per vehicle mile) are highest at very low traffic volumes, as indicated by the slope of the curves. Encroachment frequencies were found to have a local maximum for traffic volumes in the 3,000 to 5,000 average daily traffic (ADT) range. Researchers have theorized that this local maximum is the result of higher design standards associated with highways carrying higher traffic volumes, e.g., more lanes, wider lane and shoulder widths, better geometrics, etc., and an increase in driver attentiveness due to the higher traffic volumes. On the other hand, accident studies do not generally demonstrate this phenomenon, thereby raising some questions about the validity of the encroachment data collected from tire tracks.

Another approach used to collect encroachment data involved time-lapse video monitoring or electronic surveillance of highway sections. Calcote utilized time-lapse video monitoring and electronic surveillance to collect encroachment data along a number of highway sections in Texas.[11] The time-lapse video monitoring did provide visual records of all encroachments along the highway sections under observation and the characteristics of the encroachments, such as speed, angle, and lateral extent of encroachment, can be estimated from the video. However, even with the visual records, researchers still had tremendous difficulty distinguishing between controlled and uncontrolled encroachments. Many vehicles were observed to gradually move off and then back onto the traveled portion of the roadway and it was not possible to determine definitively whether these encroachments were controlled or uncontrolled. Only when the vehicle was observed to make a sudden steering or braking maneuver could one be certain that the encroachment was indeed an uncontrolled encroachment. Electronic monitoring equipment was also used in the Calcote study in a failed attempt to collect encroachment data with electronic surveillance. The electronic monitoring equipment was found to be highly unreliable. It was not possible to determine from the electronic data if the encroachments were controlled or uncontrolled or to determine the encroachment characteristics.

The high cost of video monitoring limited the study to only a few short sections of highways. Consequently, only a very small number of uncontrolled encroachments were observed. Hence, findings from this study were not considered reliable or statistically significant. However, it raised some serious questions about controlled versus uncontrolled encroachments. The study reported an extremely high ratio between controlled and uncontrolled encroachments of as much as 500 to 1 for urban freeways. If encroachment data from studies based on observations of tire tracks have comparable ratios

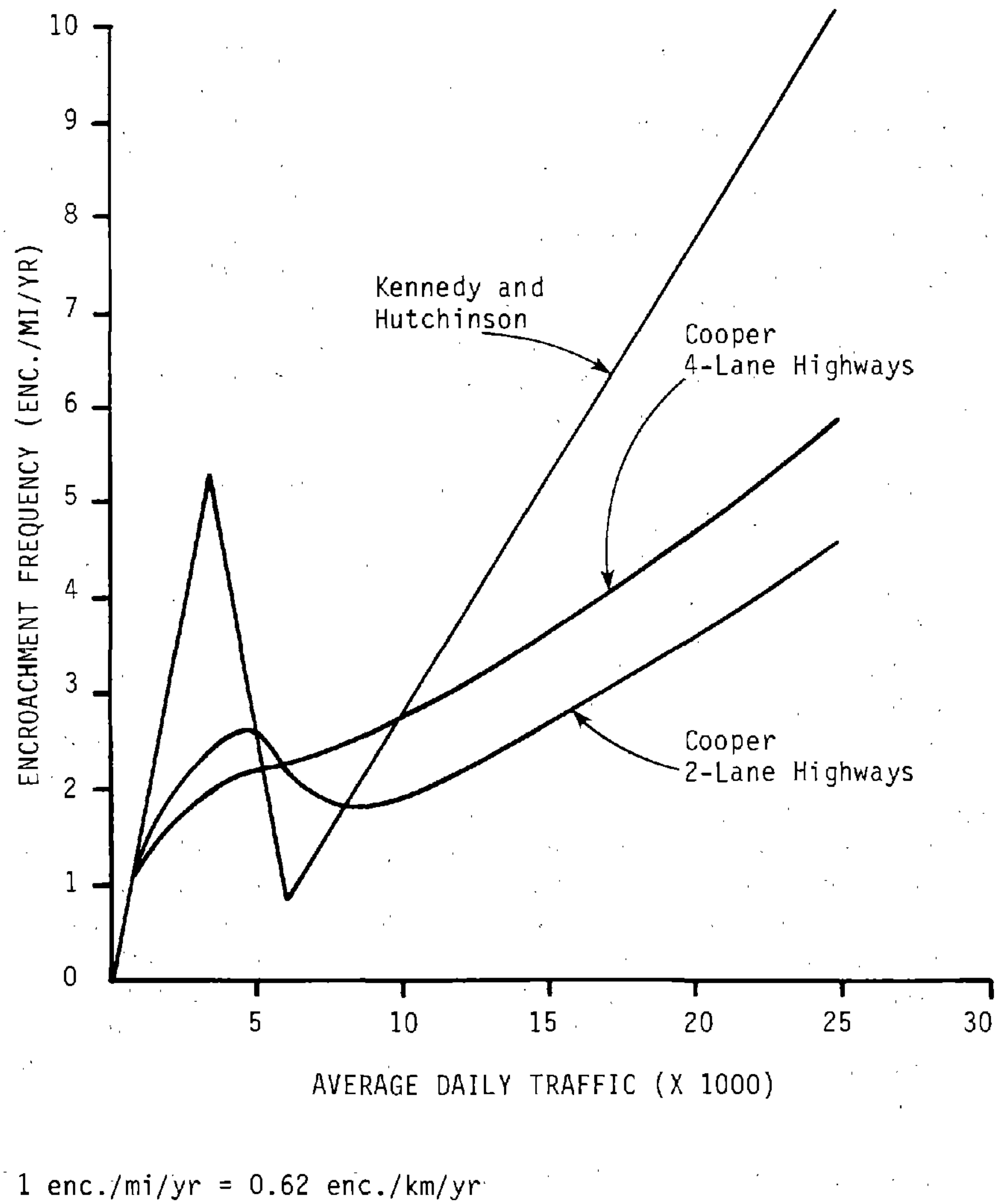


Figure 1. Encroachment frequency from studies of roadside encroachments.

between uncontrolled and controlled encroachments, encroachment frequencies and rates estimated from these studies would have little or no value.

Another concern is the change of encroachment data over time. The encroachment data collected by Kennedy and Hutchinson are over 25 years old and those by Cooper are over 10 years old. There have been significant changes in the vehicle fleet and the traffic operating characteristics during the intervening years. For example, the composition of the vehicle population has changed over the years to include a much higher proportion of smaller and lighter vehicles and multi-purpose utility vehicles, such as pickup trucks and vans, while the size and weight of trucks have increased. The handling characteristics of vehicles have improved significantly with added safety features, such as anti-lock braking systems and new tire designs that could reduce the potential for vehicle loss of control. The speed limit on highways has changed from 70 mi/h (112.7 km/h) to 55 mi/h (88.5 km/h) to 65 mi/h (104.6 km/h). All these changes could potentially have a significant effect on the encroachment frequencies/rates.

As described above, there are many unanswered questions regarding the validity of existing encroachment data. The most important of these questions is perhaps the effect of controlled encroachments on the estimated encroachment frequencies. However, these questions cannot be answered by collecting additional encroachment data using available techniques, such as observation of tire tracks. Until better and much less expensive means of collecting encroachment data become available, the collection of additional encroachment data is not recommended. Thus, some other means to check on the validity of the existing encroachment data is needed.

Reported accident data would not be a good means for validating encroachment data since only a fraction of the accidents involving roadside objects and features are actually reported to police. Many minor accidents are often not reported for a variety of reasons. Law enforcement agencies have established reporting thresholds (e.g., no injury and less than $400 property damage) below which reporting of minor traffic accidents is not required. Even when accident severity is above the minimum threshold, accidents often go unreported as a result of fear of investigations into driver fault and liability or concern over potential increases in insurance premiums. Further, law enforcement agencies in some large metropolitan areas have even adopted the policy of not reporting any property-damage-only accidents. Thus, a substantial portion of accidents are not reported by the police and are therefore not recorded in accident data monitoring systems.

While the severity of these unreported accidents is likely to be minor in nature when compared to reported accidents, it is important to know the extent of these unreported accidents, especially for evaluation of the performance of safety devices. A number of studies have examined the extent of unreported accidents with widely varying results. For example, a study on utility pole accidents found that the approximately 89 percent of all accidents were reported while another study on concrete barrier used in work zones reported that only 2 percent of accidents were reported.[12,13] Such variations indicate that the extent of unreported accidents is affected by a number of factors, including type of roadside object or feature and location. A better understanding of the extent of unreported accidents could lead to improved accident-data-based benefit-cost procedures and allow accident data to be used for validation of accident prediction models.

However, if the extent of unreported accidents is relatively low and is known or can be estimated within reasonable accuracy, then the use of reported accident data would be a viable approach for validation of encroachment data. *Transportation Research Board (TRB) Special Report 214* reports such an approach to validate and calibrate the encroachment model.[14] The conditional probabilities of a reported accident, given a collision for various roadside objects and features, were estimated using data from a study by Zegeer and Parker.[15] Once the conditional probabilities are established or assumed, it is a simple process to extrapolate the reported accident frequencies/rates to total collision frequencies/rates, which include both reported and unreported accidents. For example, the conditional probability of a reported accident given a collision for utility poles is estimated to be 0.90, i.e., 9 out of 10 collisions with utility poles would result in reported accidents. If the reported accident rate is $1.8 \times 10^{-6}$ accidents per utility pole per year, the combined reported and unreported accident rate would be $1.8/0.90 \times 10^{-6}$ or $2.0 \times 10^{-6}$ collisions per utility pole per year. The observed collision frequency/rate can then be compared to the expected collision frequency/rate based on the encroachment model for validation or calibration purposes.

It should be cautioned that these estimates on conditional probabilities have not been validated and should be used with great caution. There is reason to believe that some of these estimates are probably too high. Take utility poles as an example. The conditional probability of a reported accident given a collision for utility poles is estimated to be 0.90. In a study by Mak and Mason, reported utility pole accidents were compared to maintenance records and the ratio was found to be 0.89.[12] However, since low-speed collisions with utility poles would likely not result in damages sufficient to warrant maintenance activities, the ratio of 0.89 is probably too high. Another example is collisions with longitudinal barriers. The conditional probability of a reported accident, given a collision for longitudinal barriers, was estimated to range from 0.30 to 0.45. However, a study by Lampela and Yang found the ratio to be an order of magnitude lower at only 0.02.[13]

An alternate approach to estimate the frequency of uncontrolled encroachments is to monitor impact damage to roadside objects using field observations or maintenance records and then compare the actual to the predicted impact frequencies. This approach has previously been used to validate an encroachment probability accident prediction model by comparing maintenance records on breakaway luminaire supports with predicted accident rates.[16] This effort was very limited and the findings were not statistically significant. However, a more comprehensive effort using this approach may provide a means for validating and adjusting the base or average encroachment frequencies or rates to account for controlled and uncontrolled encroachments. Also, the data could provide estimates of the extent of unreported accidents for various roadside appurtenances.

## STUDY OBJECTIVES

The objective of the study is to validate and adjust the base or average encroachment rates used in encroachment probability-based cost-effectiveness models. Depending on the study approach used, a secondary objective of the study is to determine the extent of unreported accidents for various roadside objects.

## RESEARCH APPROACH

As discussed previously in the "Background" section, there are two alternate approaches to the conduct of this study:

1. Review reported accidents for selected roadside objects.

2. Monitor selected roadside objects for impact damage.

Brief descriptions on these two alternate approaches are presented as follows.

### First Alternate Approach

The first alternate approach for the proposed study is to review accident records on selected roadside objects and to compare the observed impact frequencies with the expected impact frequencies from the accident prediction analysis in the encroachment models. The observed and the predicted impact frequencies, when averaged over a large enough sample, should agree within reasonable limits if the base or average encroachment rates are accurate and the accident prediction analysis is appropriate. This comparison thus serves as a validation check on both the base or average encroachment rates and the accident prediction analysis procedure. If the observed and predicted impact frequencies differ significantly, the observed impact frequencies could then be used as the basis for adjusting the base or average encroachment rates and/or the accident prediction analysis procedure, as appropriate.

The major activities for this proposed research approach are as follows:

1. Identify roadway segments with selected roadside objects suitable for use in study. Categorize the roadway segments by highway type.

2. Collect records of all reported accidents involving the selected roadside objects along the roadway segments under study.

3. Compare the observed impact frequencies on these selected roadside objects to the expected impact frequencies from the encroachment models to identify any systematic errors in the accident prediction analysis of the encroachment models and to determine the base or average encroachment rates for use in the encroachment models.

More detailed descriptions on these activities are presented as follows.

## Data Requirements

The first part of the data collection effort consists of selecting specific roadside objects and features for study and making an inventory of these selected roadside objects and features along the roadway segments under study. Since the underlying assumption for this approach is that the extent of unreported accidents is very low and is known or can be estimated with reasonable accuracy, the choice of roadside objects or features for study would be limited to those that will meet this requirement, such as utility poles, vertical rock cuts, or very steep embankments. Also, the selected roadside objects and features should be located relatively close to the edge of the travelway laterally and not be shielded from impacts by longitudinal barriers or other roadside objects or features. Further, for point objects, it is desirable to select roadside objects that are uniformly spaced and relatively close together to simplify the accident prediction procedure and to minimize the probability and number of encroachments that do not result in an impact with the selected roadside object.

The other part of the data collection effort is to obtain records of reported accidents involving the selected roadside objects and features along the roadway segments under study. One approach to collecting the accident data is to ask local law enforcement agencies for copies of all accident reports that occurred within the sampled roadway segments. The accident reports are then reviewed to identify all accidents in which the selected roadside objects or features were impacted.

## Sampling Scheme

Encroachment rates are believed to be related to a number of factors, such as highway functional class, traffic volume, curvature, grade, number of lanes, lane width, shoulder width, etc. Proper evaluation of the effects of all of these factors on roadside encroachment frequency or rate would require an enormous data collection effort and would be prohibitively expensive. On the other hand, a single encroachment rate for all highway types and situations is clearly inappropriate. A compromise may be to develop separate base or average encroachment rates for different highway types. The highway type will serve as a surrogate measure for all the other factors that could potentially affect roadside encroachment frequency or rate. During the expert panel meeting, there was some discussion regarding how the highway types should be defined. One approach was to define the highway type in terms of functional class. An alternate approach was to define the highway type in terms of divided/undivided and number of lanes. After some consideration, the following six highway types are selected for use with the base or average encroachment rates:

Rural Interstates and Freeways.
Rural Multilane Undivided Highways.
Rural Two-Lane Highways.
Urban Interstates and Freeways.
Urban Multilane Undivided Highways.
Urban Two-Lane Highways.

For each highway type, typical roadway segments will be selected for inclusion in the study. Every effort should be made to select roadway segments that are typical or representative of the respective highway type. Roadway segments with unusual characteristics should be excluded. A more rigid set of selection criteria to select roadway segments that are statistically "representative" is probably not practical since the locale where these roadway segments are to be selected will be mostly a function of the contractor(s) conducting the study. However, it would be desirable, if possible, to collect the accident data from more than one geographical location so that the data may be somewhat more representative. For the sampled roadway segments, roadside objects meeting the selection criteria will then be identified for study.

The required sample size in terms of the number and total length of roadway segments to be monitored can be estimated using the following equation:

$$\nu = (Z_{\alpha/2} + Z_{\beta})^2 \lambda_o / \epsilon^2 \quad (3)$$

where
$\nu$ = Exposure (million vehicle-miles of travel)
$\lambda_o$ = Initial estimate of encroachment rate (encroachments/million vehicle miles)
$\epsilon$ = Precision, i.e., difference to be detected
$Z$ = Normalized value
$\alpha$ = Level of significance, type I error
$\beta$ = Type II error

This equation is based on a Poisson distribution for the frequency of encroachments and requires an initial estimate of the encroachment rate ($\lambda_o$), the difference to be detected ($\epsilon$), and the type I ($\alpha$) and type II ($\beta$) errors. To illustrate the application of this equation, consider the following example with:

$\lambda_o$ = 6 encroachments/million vehicle miles
$\epsilon$ = $2 \times 10^{-6}$
$\alpha$ = 0.05
$\beta$ = 0.20

The required exposure is then calculated as:

$$\nu = (Z_{0.025} + Z_{0.20})^2 \times 6 \times 10^{-6}/(2 \times 10^{-6})^2 \quad (4)$$

$$= (1.96 + 0.84)^2 \times 6 \times 10^{-6}/(2 \times 10^{-6})^2$$

$$= 11.76 \times 10^6 \text{ vehicle miles}$$

The total required exposure is $11.76 \times 10^6$ vehicle miles of travel. The total number of expected encroachments is $11.76 \times 10^6 \times 6 \times 10^{-6} = 71$. Thus, for a roadway with ADT of 10,000, a total of $11.76 \times 10^6/10{,}000 \times 365 = 3.22$ mi-yr of exposure is required. For continuous roadside features, such as vertical rock cuts and very steep embankments, the length of the continuous roadside feature to be monitored can be determined by dividing the required exposure by the length of the data collection period. For example, if the data collection period is 3 years, the length of continuous roadside feature to be monitored is 3.22/3 = 1.07 mi (1.72 km).

For point objects such as utility poles, it is necessary to first determine the length of projection of the point object onto the roadway edge by assuming an average encroachment angle. For example, using an average encroachment angle of 10 degrees, the length of projection for each point object is approximately $14/\sin(10^o) = 81$ ft (24.7 m). Again assuming a study period of 3 years, the number of utility poles to be monitored is approximately $(3.22 \times 5280)/(81 \times 3) = 70$. This can then be translated into the length of highway to be monitored by dividing the number of point objects to be monitored by the density of the object, i.e., number of objects per mile. For example, if the density of the object is 20 per mile, then the length of highway to be monitored is 70/20 = 3.5 mi (5.63 km).

An alternate method of specifying the sample size is to simply select a fixed number of encroachments to be monitored. The length of continuous roadside feature or number of point objects to be monitored can then be calculated from the estimated encroachment rate, ADT, and the length of study period, similar to the illustration shown above. For the purpose of this study, this alternate method is probably adequate and certainly much simpler to use. The recommended number of encroachments to be monitored for each highway type is 75 encroachments.

### Analytical Procedure

For each of the six highway types, the expected impact frequencies for the selected roadside objects in the sampled roadway segments will be estimated from the accident prediction analysis of the encroachment models. The observed impact frequencies on these selected roadside objects or features will then be compared to the expected impact frequencies to assess how close the observed and predicted impact frequencies would agree with each other. The comparison will also be used to identify any systematic errors in the base or average encroachment rates and in the accident prediction analysis of the encroachment models. If the observed and predicted impact frequencies differ significantly, the observed impact frequencies could then be used as the basis for adjusting the base or average encroachment rates and/or the accident prediction analysis procedure, as may be appropriate.

## Second Alternate Approach

The second alternate approach for the proposed study is to monitor selected roadside objects for impact damage and to collect accident records on these monitored roadside objects. The observed impact frequencies with these selected roadside objects will be compared to the expected impact frequencies from the accident prediction analysis in the encroachment models. The observed and the predicted impact frequencies, when averaged over a large enough sample, should agree within reasonable limits if the base or average encroachment rates are accurate and the accident prediction analysis is appropriate. This comparison thus serves as a validation check on both the base or average encroachment rates and the accident prediction analysis procedure. If the observed and predicted impact frequencies differ significantly, the observed impact frequencies could then be used as the basis for adjusting the base or average encroachment rates and/or the accident prediction analysis procedure, as appropriate.

Data from the study can also be used to determine the magnitude of the unreported accident problem for the selected roadside objects. Records of all accidents involving the selected roadside objects along the roadway segments under study would be compared to the observed impacts to determine what proportion of the observed impacts were actually reported to law enforcement agencies. Note that the extent of unreported accidents is likely to differ among different roadside objects and the results from the study would thus be limited only to those roadside objects included in the study.

The major activities for this proposed research study are as follows:

1. Identify roadway segments with selected roadside objects suitable for use in study. Categorize the roadway segments by highway type.

2. Monitor impact damage on the selected roadside objects within the sampled roadway segments.

3. Collect records of all reported accidents involving the selected roadside objects along the roadway segments under study.

4. Compare the observed impact frequencies on these selected roadside objects to the expected impact frequencies from the encroachment models to identify any systematic errors in the accident prediction analysis of the encroachment models and to determine the base or average encroachment rates for use in the encroachment models.

5. Compare the records of reported accidents to the observed impact frequencies to determine the extent of unreported accidents for the selected roadside objects.

More detailed descriptions on these activities are presented as follows.

## Data Requirements

The first part of the data collection effort will consist of monitoring selected roadside objects for impact damage and to collect records of reported accidents on these monitored roadside objects. Monitoring of impact damage could take two different forms: (1) review of maintenance records for roadside objects that are easily damaged even in very minor impacts, and (2) periodic inspection of roadside objects with easily identifiable evidence of impacts.

For roadside objects that are easily damaged by even minor impacts, such as breakaway luminaire supports, monitoring of impacts could be accomplished through review of maintenance records. The underlying assumption is that every impact with the roadside object would result in sufficient damage to warrant some form of maintenance activity. To ensure a valid analysis, the roadside objects selected for monitoring should be located relatively close to the edge of the travelway laterally and not be shielded from impacts by longitudinal barriers or other roadside objects or features. Further, it is desirable to select roadside objects that are uniformly spaced and relatively close together to simplify the accident prediction procedure and to minimize the probability and number of encroachments that do not result in an impact with the selected roadside object.

Note that there are some limitations to this approach. The accuracy of the encroachment data is only as good as that of the maintenance records. Also, some of the impacts may not be severe enough to be noticed or warrant maintenance activities. The availability of the selected roadside objects may limit the study to only certain types of roadways. Furthermore, if the selected roadside objects are located too far from the edge of the travelway or are not spaced closely enough, the impact frequency could be expected to be very low, and an excessively long period of monitoring would be required to obtain a sufficient sample size. On the other hand, if accurate maintenance records are kept by the highway agency, many years of data can be included in the study with little associated effort.

Some roadside objects, such as longitudinal barriers and fences, are usually not damaged sufficiently to require maintenance for every impact, but the impacts would leave some easily identifiable evidence, such as tire marks, paint scrapes, or minor damage to the roadside objects. Impact frequencies with these roadside objects could be monitored by periodically inspecting the roadside objects for evidence of impact damage. The accuracy of this approach should be fairly good, but not without its problems. For example, evidence from some impacts may be too minor to be noticed or an errant vehicle may impact the barrier more than once in the impact sequence and thus be counted as more than one incident. Sample size is expected to be less of a problem for these continuous roadside objects since they are deployed much more frequently than point objects and a sufficient sample size could be collected in a shorter period of time. The biggest drawback with this approach is that it is labor intensive, thus resulting in high costs for the data collection effort.

The other part of the data collection effort is to obtain records of reported accidents involving the selected roadside objects along the roadway segments under study. The data collection period for the accident records should be the same as that for impact damage data for comparison purposes. One approach to collecting the accident data is to ask local law enforcement agencies for copies of all accident reports that occurred within the sampled roadway segments. The accident reports are then reviewed to identify all accidents in which the selected roadway objects were impacted. The accidents are then compared and matched to the maintenance records or observed impact damage to determine what proportion of the impacts was actually reported to law enforcement agencies.

Sampling Scheme

Similar to the first alternate approach, the following six highway types will be used with the base or average encroachment rates:

Rural Interstates and Freeways.
Rural Multilane Undivided Highways.

Rural Two-Lane Highways.
Urban Interstates and Freeways.
Urban Multilane Undivided Highways.
Urban Two-Lane Highways.

For each highway type, typical roadway segments will be selected for inclusion in the study. Every effort should be made to select roadway segments that are typical or representative of the respective highway type. Roadway segments with unusual characteristics should be excluded. A more rigid set of selection criteria to select roadway segments that are statistically "representative" is deemed not practical. However, it would be desirable, if possible, to collect the accident data from more than one geographical location so that the data may be somewhat more representative.

For the sampled roadway segments, roadside objects meeting the selection criteria will be identified for monitoring. As discussed previously under "Data Requirements," the selection criteria for point objects, such as breakaway luminaire supports, are: (1) likely to be damaged to the extent of requiring maintenance from any impact by an encroaching vehicle, (2) located close to the travelway, and (3) closely spaced so that any encroachment will likely result in an impact with the point object. For continuous objects, such as longitudinal barriers and fences, the only requirement is that they be located close to the travelway.

As discussed previously under the first alternate approach, the required sample size can be expressed in terms of the number and total length of roadway segments to be monitored or in terms of a fixed number of encroachments to be monitored. The procedure and approach for determining the required sample size length will be the same as that for the first alternate approach and will not be repeated herein. Again, for the purpose of this study, the alternate method of specifying a fixed number of encroachments to be monitored is probably adequate and certainly much simpler to use. The recommended number of encroachments to be monitored for each highway type is 75 encroachments.

## Analytical Procedure

For each of the six highway types, the expected impact frequencies for the selected roadside objects in the sampled roadway segments will be estimated from the accident prediction analysis of the encroachment models. The observed impact frequencies on these selected roadside objects will then be compared to the expected impact frequencies to assess how close the observed and predicted impact frequencies would agree with each other. The comparison will also be used to identify any systematic errors in the base or average encroachment rates and in the accident prediction analysis of the encroachment models. If the observed and predicted impact frequencies differ significantly, the observed impact frequencies could then be used as the basis for adjusting the base or average encroachment rates and/or the accident prediction analysis procedure, as may be appropriate.

To determine the extent of the unreported accidents, accident records are compared and matched to the observed impact frequencies to determine the proportion of the observed impact frequencies that is not reported to the law enforcement agencies. This analysis will be conducted for each of the selected roadside objects and each of the six highway types.

## ANTICIPATED RESULTS

The anticipated results from the study are:

1. Validation of encroachment frequency and rate for use in the cost-effectiveness model.

2. A basis for calibrating or adjusting the encroachment frequency and rate for use in the cost-effectiveness model.

If the second alternate approach is used, the study will also provide a better understanding of and data on the extent of unreported accidents for the roadside objects and features selected for study.

## ESTIMATED COST AND TIME

### First Alternate Approach

Estimated Cost: $100,000

Estimated Time: 24 months

### Second Alternate Approach

Estimated Cost: $300,000

Estimated Time: 40 months

# APPENDIX B. DETERMINATION OF ENCROACHMENT FREQUENCY/RATE ADJUSTMENT FACTORS

## BACKGROUND

Encroachment rate is likely affected by various geometric and roadway characteristics, such as horizontal and vertical alignments, number of lanes, etc. The base encroachment rates used as initial inputs to the benefit/cost analysis model are average values and do not account for variations of these characteristics at individual sites. Thus, it is necessary to adjust the base encroachment rates to reflect specific site conditions. One approach is the use of empirical adjustment factors.

The Benefit Cost Analysis Program (BCAP) uses empirical adjustment factors to account for horizontal curvature and vertical grade. The user inputs the site conditions and the BCAP program applies these adjustments to the average daily traffic (ADT). The adjustment factor for horizontal curvature is a function of the location relative to the curve and the degree of curvature. The adjustment factor ranges from 1.0 (unchanged) to a high of 4.0, shown as follows:

| Location | Degree of Curvature | Adjustment Factor |
| --- | --- | --- |
| Outside | $>= 6.0$ | 4.0 |
| | $6.0 > x > 3.0$ | 4 - (6 - x) |
| | $<= 3.0$ | 1.0 |
| Inside | $>= 6.0$ | 2.0 |
| | $6.0 > x > 3.0$ | 2 - (6 - x)/3 |
| | $<= 3.0$ | 1.0 |

where x is the degree of curvature.

The adjustment factor for vertical grade is a function of the type of grade as well as the percent grade. The adjustment factor ranges from 1.0 (unchanged) to a high of 2.0, shown as follows:

| Grade | Percent Grade | Adjustment Factor |
| --- | --- | --- |
| Upgrade | - | 1.0 |
| Downgrade | $<= 2.0$ | 1.0 |
| | $2.0 < x < 6.0$ | 2 - (6 - x)/4 |
| | $>= 6.0$ | 2.0 |

where x is the percent grade.

These adjustment factors are based on a study by Wright and Robertson in which 300 fatal single-vehicle, ran-off-the-road, fixed-object accidents were studied.[17] Horizontal and vertical alignment at these fatal accident sites were compared to control sites located 1 mi (1.61 km) upstream of the accident sites to determine the effect of horizontal and vertical alignment. The basic premises of the study design are: (1) the control sites are representative of the average highway and (2) if horizontal and vertical alignment have no effect on the fatal accidents, it is reasonable to expect that the distributions of horizontal and vertical alignment would approximate those of the control sites. The study found that the presence as well as the severity of horizontal curves and vertical grades, particularly the interactions, were over-represented at the fatal accident sites when compared to the control sites. The empirical adjustment factors for horizontal and vertical alignment used in the BCAP program were derived from the study results.

While the study was well designed, it has a very small sample size and the effects of horizontal and vertical alignment are likely over-estimated since the study included only fatal accidents. Also, there may be additional roadway characteristics that could potentially affect encroachment rates that were not included in the adjustment factors. In order to account for roadway characteristics that may have significant effect on encroachment frequency and rate, there is a need to identify these roadway characteristics and to develop the appropriate empirical adjustment factors.

## STUDY OBJECTIVES

The objectives of the study are to:

1. Identify geometric and roadway characteristics that have significant effects on encroachment frequency and rate.

2. Determine appropriate adjustment factors for these geometric and roadway characteristics.

## RESEARCH APPROACH

The basic concept to this proposed research approach is very straight forward. The objectives of the study are to identify geometric and roadway characteristics that have significant effects on encroachment frequency and rate and to quantify their relationships. However, until some better and much less expensive means of collecting encroachment data becomes available, it is simply not feasible to study encroachments directly. Thus, a surrogate measure for encroachment will have to be used for the analysis. The surrogate measure selected is single-vehicle, ran-off-the-road type accidents.

It can be reasoned that single-vehicle, ran-off-the-road type accident rates (herein referred to simply as accident rates) are affected by the same geometric and roadway characteristics that influence encroachment rates. The key difference is that accident rates are also affected by roadside conditions, such as the density and offset of roadside obstacles. It is therefore necessary to neutralize the effect of roadside conditions in order to isolate the effect of geometric and roadway characteristics. This can be accomplished by carefully selecting study and comparison sites with similar roadside conditions, i.e., clear zone width, sideslope, nature and density of roadside objects, etc. If the roadside conditions are similar between the study and comparison sites, it can be argued that the effect of roadside conditions would be the same for both the study and comparison sites and therefore cancel out each other. Thus, the comparisons on accident rates among roadway segments with and without a specific geometric or roadway characteristic would not be affected by roadside conditions and single-vehicle, ran-off-the-road type accident rates are a good surrogate for encroachment rates under these circumstances.

The same argument can be used for other potential built-in biases with reported accident data, such as reporting threshold and the extent of unreported accidents. The effects of the biases should be similar for the study and comparison sites and their effects would neutralize each other and not affect the analysis. It is recognized that there are potential problems and biases with the use of single-vehicle, ran-off-road type accident rates as a surrogate for encroachment rates. However, given that collecting encroachment data is not a viable option at this time, this approach of using single-vehicle, ran-off-road type accident rates as a surrogate for encroachment rates is a reasonable alterative to obtain the needed information on the effects of geometric and roadway characteristics on encroachment rates.

The basic approach for the proposed study is to compare accident rates among roadway segments with and without a specific geometric or roadway characteristic after controlling for other influencing factors or co-variates, especially roadside conditions, so that one can ascertain if that specific geometric or roadway characteristic has any significant effect on the accident rates and also to quantify the effect. The manner in which the effect is quantified can range from a simple ratioing of the accident rates to determine empirical adjustment factors to more complicated statistical modelling to develop predictive models.

The major activities for this proposed research study are as follows:

1. Identify a suitable data base or data bases for use with the study.

2. Categorize the highways by highway type, similar to that used for the base encroachment rates. For each highway type, the highways are then broken down into homogeneous roadway segments.

3. Match accidents to the roadway segments through a location matching process. Calculate the accident frequencies and rates for the individual roadway segments.

4. Compare the accident frequencies and rates for the various geometric and roadway characteristics to identify characteristics that have significant effect on the accident rates and to develop empirical adjustment factors for these characteristics.

More detailed descriptions on these activities are presented as follows.

## Data Requirements

It is believed that the Highway Safety Information System (HSIS) data base, with limited additional data collection effort, could be used for this analysis. Other existing data bases, such as the data base developed for the study, *Safety Effects of Cross-Section Design for Two-Lane Roads*, could also be used for parts of the analysis.[18] The basic requirements for the data base needed for this analysis are as follows:

1. The data base should be location-based, so that the highways can be broken down into homogeneous roadway segments.

2. The data base should contain detailed information on geometric and roadway characteristics. As a minimum, information should be available on the following data elements:

   Average Daily Traffic.
   Horizontal Curvature.
   Vertical Grade.
   Number of Lanes.
   Lane Width.
   Presence/Absence of Median and Median Width.
   Presence/Absence of Paved Shoulder and Shoulder Width.
   Presence/Absence of Intersection.

3. The data base should have the capability of allowing accident data to be matched with the roadway segments through a location-matching process.

4. The data base should have some information on the roadside conditions, such as clear zone width, sideslopes, roadside hazard rating, etc. If this information is not available from the data base, there should be available some means of collecting this information inexpensively from other sources, such as photologs of the highways. It should be borne in mind that the

information on roadside conditions does not need to be precise since the purpose is to select roadway segments with similar roadside conditions.

If the existing HSIS data base is used with this analysis with some minor additional data collection effort, the sample size or the number of roadway segments required for the analysis becomes a moot question. The cost for including the entire data base (or at least some of the States in the data base with the required data) will only be marginally higher than that of using a sample from the data base since the only differences are computer time to process the data and the time required to review photologs. In other words, the sampling scheme is simply to include as many roadway segments as available that meet the study criteria, especially with regard to similar roadside conditions.

**Categorization Scheme**

The highways will first be categorized by highway type, using the same scheme as that for determining the encroachment base rates (see proposed study 1 in appendix A for details). It is anticipated that the following six highway types will be used for the encroachment base rates:

Rural Interstates and Freeways.
Rural Multilane Undivided Highways.
Rural Two-Lane Highways.
Urban Interstates and Freeways.
Urban Multilane Undivided Highways.
Urban Two-Lane Highways.

In other words, since a different base encroachment rate will be developed for each of these six highway types, it is just logical that different adjustment factors will be developed for each of the six highway types and the associated base encroachment rates.

Within each highway type, the highways will first be screened for similar roadside conditions, i.e., clear zone width, sideslope, and roadside hazard rating. As noted previously, the intent is to make sure that the highway segments selected for study have similar roadside conditions to neutralize the potential effect of roadside conditions on the accident rates. It is envisioned that the roadside conditions will be defined in terms of relatively wide ranges, e.g., 10 to 20 ft (3.05 to 6.1 m) in clear zone width, sideslopes of 4:1 or flatter, and a roadside hazard rating of 3 to 7. Thus, the screening could be cursory in nature without the need for actual measurements. The reasoning for such latitude in defining roadside conditions is that, given a large enough sample size, the variations in the individual sites will basically even out over the long run. This is particularly true in this case since the study and the comparison sites are not pre-defined so that it is likely that both the study and comparison sites will be selected from the same highways.

After the screening, the highways will be broken down into homogeneous roadway segments for analysis. There are three alternate approaches to create these homogeneous roadway segments. The first approach is to break down the highways into short segments of fixed length, e.g., 1.0 mi (1.61 km). For each roadway segment, the geometric and roadway characteristics will be checked for homogeneity. Roadway segments that are not homogeneous in terms of cross-sectional data elements, such as changing from two to four lanes, or divided to undivided roadway, will be eliminated so that each roadway segment is relatively homogeneous. For the horizontal and vertical alignment data elements, the maximum degree of curvature and maximum grade will be noted for each roadway segment.

The second approach is to move down the highway and mark the roadway segments every time there is a change in any of the geometric or roadway data elements. This approach is more difficult to execute from both the logistic and programming standpoints, but would produce roadway segments that are more homogeneous than the first approach. The major problem is that this requires a pre-determination of which geometric or roadway characteristic(s) would affect the encroachment rates. As such, it may not be possible to analyze the effects of other geometric or roadway characteristics not included in the definition of homogeneity for the roadway segments. Another drawback with this approach is that the segment lengths will be non-uniform and some of the segments, particularly those associated with changes in horizontal or vertical alignment, may be too short for meaningful analysis. Further, the unequal segment lengths will slightly complicate the analysis since the accident rates will have to be weighted by the segment lengths in order to account for the unequal segment lengths.

A third approach is to use the unit length in the roadway inventory file as the length of a roadway segment. For example, the roadway inventory file for the State of Texas reports roadway data every 0.1 mi (161 m), which means that the length of each roadway segment is 0.1 mi (161 m). This approach greatly simplifies the programming effort since homogeneity within a roadway segment is no longer a concern given the short unit length. The analytical procedure with this approach would be different from the other two approaches since accident frequency and rate will not be calculated for each individual segment, but only in aggregate. This approach has been successfully applied in a study to evaluate the effects of lane width on accident rates.[19]

The researchers conducting the study will have to determine which of the three alternate categorization scheme is the best with the HSIS data base or any other data base used in the study, perhaps through some form of a pilot study.

**Analytical Procedure**

For each roadway segment, single-vehicle, ran-off-the-road type accidents will be matched to the roadway segment using a location matching process. The accident data should probably cover a minimum period of 3 years. The key consideration is to ensure that the number of accidents per roadway segment is large enough to provide stable results. Again, this is probably best determined through a pilot study. Note that the number of accidents per roadway segment can be varied by changing the length of the roadway segment and/or the number of years of accident data.

Accident frequency, expressed as number of accidents per year per mile of highway, and accident rates, expressed as number of accidents per million vehicle-miles of travel, will then be determined for the roadway segments:

$$\text{Accident Frequency} = \frac{\text{Number of Accidents}}{\text{No. of Years x Segment Length}} \quad (5)$$

$$\text{Accident Rate} = \frac{\text{Number of Accidents}}{\text{365 x ADT x No. of Years x Segment Length}} \times 10^6 \quad (6)$$

There are two analysis approaches that can be used separately or in combination. One approach is Poisson regression analysis in which accident frequency or rate, the dependent variable, will be regressed against the various geometric and roadway characteristics, the independent variables. Using a stepwise procedure, the effect of each geometric or roadway characteristic can be tested for statistical significance. For those geometric and/or roadway characteristics that are found to be statistically significant, adjustment factors can then be developed by ratioing the predicted accident rates from the regression models.

The other analysis approach is more heuristic in nature and more dependent on the ability of the analyst to extract the proper results. The analysis will begin by comparing the observed accident frequencies or rates for each of the geometric and roadway characteristics, e.g., straight versus curve, level versus grade, etc., to first identify which geometric or roadway characteristics have significant effect on the accident rates. For those geometric and/or roadway characteristics that are found to have significant main effects, the evaluation will continue for the first order interactions, i.e., combinations of two variables, among these significant characteristics, e.g., straight and level versus curve and grade, etc. This process will be repeated for the higher order interactions, adding one variable at a time, until all combinations have been evaluated or, more likely, until the sample sizes for the individual cells become too small for meaningful analysis. The adjustment factors will simply be the ratios between the observed accident rates for that individual or combination of geometric and/or roadway characteristics. This approach allows more input and interpretation from the analyst, who may be better able to identify trends and causal relationships than by just looking at a regression equation.

Note that the analysis will be repeated for each of the six highway types, i.e., adjustment factors will be developed for each highway type and the associated base encroachment rate.

## ANTICIPATED RESULTS

The anticipated results from the study are:

1. A list of geometric and/or roadway characteristics that have significant effect on the encroachment rate for each highway type and associated base encroachment rate.

2. Appropriate adjustment factors for these significant geometric and/or roadway characteristics for each highway type and associated base encroachment rate.

## ESTIMATED COST AND TIME

Estimated Cost: $200,000

Estimated Time: 24 Months

# APPENDIX C. EFFECT OF ROADSIDE CONDITIONS ON IMPACT PROBABILITY AND SEVERITY

## BACKGROUND

All previous encroachment probability models have not incorporated the effect of roadside conditions, e.g., sideslope, ditch configuration, etc., into the determination of impact probability and severity. Yet it is intuitive that roadside conditions could have significant effects on the trajectory of an errant vehicle after it leaves the roadway and on the ability of a driver to maintain control of the vehicle and to recover from the errant path.

Furthermore, rollover accidents account for a large portion of roadside accidents. For example, approximately one-third of all fatal single-vehicle ran-off-the-road accidents have rollover as the most harmful event. While some of these rollover accidents resulted from impact with roadside objects and features, a significant portion of these rollover accidents did not. It is reasonable to assume that roadside conditions may contribute to the occurrence of such rollover accidents. Given the magnitude and the higher than average severity of rollover accidents, there is a need for better understanding and quantification of the effects of roadside conditions on impact probability and severity, particularly rollover accidents.

The major effects of roadside conditions on impact probability and severity are expected to be:

1. Extent of lateral encroachment, i.e., the lateral distance an errant vehicle would travel after encroaching into the roadside.

2. Performance of roadside safety appurtenances, e.g., guardrail, breakaway devices, etc.

3. Rollover accidents.

Brief discussions on each of these effects are presented as follows.

### Extent of Lateral Encroachment

It is intuitively apparent that the steepness of the sideslope should have significant effect on the extent of lateral encroachment of an errant vehicle after it leaves the roadway and on the ability of a driver to maintain control of the vehicle and to recover from the errant path. The extent of lateral encroachment would in turn affect the probability of an errant vehicle impacting roadside hazards. In a study to assess the effect of sideslopes on the clear zone distance requirement, the responses of selected passenger cars on a range of sideslopes were studied for selected encroachment conditions and driver inputs.[20] The study results clearly indicate that the extent of lateral encroachment is significantly affected by the sideslopes.

The effect of sideslope on the lateral extent of encroachment is best studied with encroachment data. However, until some better and much less expensive means of collecting encroachment data becomes available, it is simply not feasible to study encroachments directly. A surrogate measure, such as evidence of impact from field observations and/or maintenance records (see proposed study 1 in appendix A), or single-vehicle, ran-off-the-road accidents (see proposed study 2 in appendix B), is typically used for the analysis with the assumption that there is a direct relationship between encroachment and the surrogate measure. However, for the purpose of studying the extent of lateral encroachment, these surrogate measures are not appropriate since the extent of lateral encroachment is limited by the clear zone distance, or the lateral offset of roadside objects and features. For example, assume that the extent of lateral encroachment for an errant vehicle is increased from 20 to 30 ft (6.1 to 9.1 m) due to the sideslope. If the clear zone is only 15 ft (4.6 m), the effect of this increase in extent of lateral encroachment will not be manifested by the surrogate measures since 15 ft (4.6 m) is the maximum lateral distance an errant vehicle could travel prior to impacting with some roadside object or feature.

A computer simulation study, similar to the previous study mentioned above, would be a better approach in terms of studying the effects of sideslopes on the extent of lateral encroachment and is therefore recommended.[20] Details of the proposed study are presented in the "Research Approach" section.

## Performance of Roadside Safety Appurtenances

Roadside conditions could have a significant effect on the performance and the resulting impact severity of some roadside safety appurtenances. For example, it has been shown that guardrails installed on sideslopes may not perform properly, thus increasing the probability of an impacting vehicle vaulting or going over the guardrail with higher resulting injury severity. While it is recognized that roadside conditions could affect the performance of some roadside safety appurtenances, it is questionable as to whether the effects can be studied in a cost-effective manner.

First, indepth accident data will be required to provide the needed level of detail for the reconstruction and clinical evaluation of the accidents. Second, the process to determine how much, if any, the roadside conditions affected the performance of the roadside safety device is very difficult and subjective as well as very time consuming. There are so many other variables that could potentially affect the performance of roadside safety appurtenances that it may be difficult to isolate the effects due to roadside conditions. In summary, it is felt that the chance of success for a study to determine the effects of roadside conditions on the performance of roadside safety appurtenances is very poor and thus not recommended.

**Rollover Accidents**

It is reasonable to assume that roadside conditions contribute to the occurrence of rollover accidents. For example, a steeper sideslope would increase the roll angle of an errant vehicle, thus rendering it more susceptible to rollovers. However, it has been found in previous studies that the rollover phenomenon is a very complicated process and highly unpredictable, particularly with respect to the tripping mechanism.[21] Again, it would be difficult, if not impossible, to isolate only the effects due to roadside conditions. Also, it would be questionable as to whether the results can be effectively incorporated into the roadside safety cost-effectiveness model. One exception is the severity associated with sideslopes.

In the roadside safety cost-effectiveness model, sideslope is considered a roadside feature with an associated severity rating. It can be argued that the severity associated with a sideslope is totally the result of rollover accidents, assuming that the errant vehicle does not impact with another roadside object or feature. In other words, assuming that the sideslope is of infinite width and totally free of other roadside objects or features, the only harm that could happen to an errant vehicle on the sideslope is for the vehicle to roll over. A study to determine the probability and severity of rollover accidents for various sideslopes is therefore proposed. Details of the proposed study are presented in the "Research Approach" section.

While further study to determine the effect of roadside conditions on rollover accidents is not recommended, a comprehensive study to better understand rollover accidents and to devise potential countermeasures is highly recommended. This comprehensive study should be a high priority research topic given the magnitude of the problem and the higher than average severity of rollover accidents. However, the study should look at all aspects of rollover accidents and not only the effects of roadside conditions. While such a study on rollover accidents is considered very important and highly recommended, it does not fit into the scope of this study. A detailed data collection plan is therefore not developed for this rollover study.

**Summary**

The scope of work under this proposed research topic on the effects of roadside conditions on impact probability and severity has been narrowed down to two specific and separate studies. The first study is to determine the effects of sideslopes on the extent of lateral encroachment through computer simulation. The second study is to determine the severity associated with various sideslopes.

## STUDY OBJECTIVES

The objectives of the study are to:

1. Determine the effect of sideslopes on the extent of lateral encroachment.

2. Determine the severity associated with various sideslopes.

## RESEARCH APPROACH

As mentioned previously, there are two distinct and separate analyses under this research study. Discussions on the research approaches for the two analyses will be presented separately.

### Extent of Lateral Encroachment

The first analysis is to determine the effects of sideslopes on the extent of lateral encroachment using computer simulation. The Highway-Vehicle-Object Simulation Program (HVOSM) would work well in this simulation effort. The basic approach for this study is very straightforward. For a given sideslope, the trajectory of an errant vehicle will be simulated using the HVOSM program to estimate the extent of lateral encroachment for various design vehicles under certain pre-determined encroachment conditions and driver inputs. This process will be repeated for various sideslopes and the results compared to determine the effects of sideslopes on the extent of lateral encroachment.

Simulation Matrix

The most critical part of the study design is the simulation matrix, which should include, as a minimum, the following parameters:

1. Design vehicles.
2. Design encroachment conditions.
3. Driver inputs.
4. Friction.
5. Highway Cross-Sectional Layout.

Brief discussions on each of these parameters are presented as follows.

Design Vehicles. There are four basic design vehicles currently in use on the crash testing and evaluation of roadside safety appurtenances: (1) an 1,800-lb (817-kg) passenger car, (2) a 4,500-lb (2,043-kg) passenger car or pickup truck, (3) an 18,000-lb (8,170-kg) single unit truck, and (4) a 50,000-lb (22,665-kg) or 80,000-lb (36,265-kg) tractor-trailer. For the purpose of this simulation effort, the 1,800-lb (817-kg) passenger car and the 4,500-lb (2,043-kg) pickup truck are recommended as the design vehicles.

Design Encroachment Conditions. The simulation matrix should ideally cover different encroachment conditions. However, since there is currently no good information on the encroachment conditions, a surrogate measure, such as impact conditions (i.e., impact speed and angle and vehicle orientation), will have to be used. It is recommended that three levels of encroachment conditions be included in the simulation matrix: (1) low (15th percentile), (2) median (50th percentile), and (3) high (85th percentile)

Driver Inputs. Driver inputs after encroaching into the roadside can range from doing nothing to maximum steering and/or braking in attempts to return to the travelway and/or come to a safe stop. If the driver does nothing, the vehicle will simply keep on going until impact with a roadside object or feature. It is really immaterial as to what the sideslope is in this case. The more likely scenario is for the driver to panic and apply maximum steering and/or braking to the vehicle. Except for a small proportion of expert drivers, it is unlikely for a driver in panic to use moderate amounts of steering and braking in combination. For vehicle equipped with antilock brake systems, it is possible for the driver to apply maximum steering and maximum braking simultaneously. However, the HVOSM program cannot currently handle vehicles with antilock brake systems. Another consideration is that a significant proportion of the encroaching vehicles are already out of control, i.e., the driver is no longer in control of the vehicle and any driver input is likely to be erratic and unpredictable. The HVOSM program does have the capability to handle non-tracking vehicles, but there is insufficient information to estimate or predict the likely driver inputs. Thus, the two scenarios recommended for use with the simulation matrix are: (1) maximum steering, and (2) maximum braking.

Friction. Vehicle response to driver inputs of steering and braking is significantly affected by the available friction between the vehicle tires and the surface. The roadside area, including sideslopes, are typically covered with grass. The coefficient of friction of the grassy surface is affected by many factors, such as the type, density and length of the grass, the presence/absence of moisture on the grass, etc. For the simulation effort, the use of two typical frictional levels are recommended: (1) dry grassy surface, and (2) wet grassy surface.

Highway Cross-Sectional Layout. A typical highway cross-sectional layout includes: shoulder width and type, sideslope, ditch configuration, and backslope. Also, the width of the clear zone would limit the maximum extent of lateral encroachment. However, to include all these cross-sectional parameters would greatly complicate the simulation effort. Thus, for the purpose of this initial simulation effort, it is recommended that the highway cross section layout be limited to a shoulder with a 10:1 cross slope and the sideslope. The sideslope is assumed to either have an infinite width or a limited width with a flat surface at the bottom. If the initial simulation effort is successful in providing useful information for formulation of the cost-effectiveness model, a continuing study may then be initiated to include a more realistic simulation of the highway cross-sectional layout.

Summary. For each sideslope, the simulation matrix would therefore consist of: 2 design vehicles, 3 encroachment conditions, 2 driver input scenarios, and 2 frictional levels, for a total of 24 simulation runs. Assuming that the study will cover five different sideslopes, i.e., 2:1, 3:1, 4:1, 6:1, and 10:1, the total number of simulation runs for the entire study would be (5 x 24) or 120 runs.

Analytical Procedure

The extent of lateral encroachment for the various combinations of design vehicle, encroachment condition, and driver input will be tabulated for each sideslope under study. The results will then be compared among the various sideslopes to assess the effects of sideslopes on the extent of lateral encroachment. Depending on the results of the simulation study, empirical adjustment factors or revised extent of lateral encroachment curves can be developed for use with the various sideslopes. Note that this analytical process is not statistical, but mainly heuristic in nature.

**Severity of Sideslopes**

The second analysis is to determine the severity associated with various sideslopes. The basic approach for the proposed study is to determine the probability of rollover accidents for various sideslopes after controlling for other influencing factors, such as highway type, clear zone distance, presence/ absence of shoulder and shoulder width, vehicle type and weight, etc. The severity of various sideslopes are then determined by combining the probability with the expected severity of rollover accidents. The underlying assumption of the proposed research approach is that the severity of sideslopes is totally determined by the probability and severity of rollover accidents.

The major activities for this proposed research study are as follows:

1. Create a data base suitable for use with this study.

2. Determine the probability of rollover accidents for the various sideslopes after controlling for other influencing factors.

3. Determine the severity associated with the rollover accidents for the various sideslopes after controlling for other influencing factors.

More detailed descriptions on these activities are presented as follows.

Data Requirements

It is believed that the data base developed for the study by Zegeer, et al., "Safety Effects of Cross-Section Design for Two-Lane Roads" would be a good starting point for this analysis.[18] The limitation with this data base is that it included only rural two-lane highways. Also, the information available on sideslopes is very gross with measurements on sideslopes taken only every 1/4 mi (402 m). For more accurate information on the sideslopes, additional data collection will be required. An alternate is to use the Highway Safety Information System (HSIS) data base. Using the HSIS data base would permit the study of the severity of sideslopes for each of the six highway types used with the base encroachment rates. However, roadside data are not available in the HSIS data base and it will be necessary to collect data on roadside data elements.

Field collection of accurate roadside data is an expensive and time-consuming effort. Given that the study deals with only the severity of sideslopes, which is one of the many roadside objects and features, it cannot justify the costs associated with the additional data collection. Thus, unless there are other reasons to collect more accurate data on roadside slopes, it is assumed in development of the research approach that the existing data base from the Zegeer study (herein referred to simply as the data base) will be used for the analysis without any additional data collection effort.

The data base is location-based and contains data on 1,944 sections of two-lane highways from 7 States, a total of 4,951.28 mi (7,968.3 km). The sampled highways were all two-lane roadways, but they covered a wide range of traffic and geometric conditions. Sideslope information was available on only 595 roadway sections from Alabama, Michigan, and Washington, totalling 1,776 mi (2,858 km).

Analytical Procedure

The Zegeer study attempted to address the effects of sideslopes on single vehicle and rollover accidents. Log linear regression models relating single-vehicle and rollover accident rates to sideslopes and other roadway, roadside and traffic parameters (including lane width, recovery distance, average daily traffic, and shoulder width) were developed to estimate the effects of sideslopes on rollover accidents. The $R^2$ values, i.e., the proportion of total variations explained by the regression equation, for these models were very low, e.g., the $R^2$ value for the single vehicle accident rate model was only 0.19, meaning that the model explained only a small percentage of the variations in the accident rates. More importantly, the models did not take vehicle type and weight into account, which are critical factors as far as rollover accidents are concerned.

In order to take vehicle type and weight into account, the analysis would necessarily be accident based. This would require converting the data base from a location-based format to an accident-based format. First, single-vehicle, ran-off-the-road type accidents will be matched to the roadway sections through a location matching process. For each of these accidents, roadway, roadside and traffic data elements will be merged with the accident data to create a new accident-based data file.

The standard logistic regression procedure will be used for the analysis. For each accident, rollover, the dependent variable, is treated as a discrete, binary variable, i.e., 1 = rollover and 0 = not rollover. Note that a rollover accident is defined as one in which rollover is the first harmful event. Accidents in which the vehicle struck another roadside object or feature and then rolled over would not be considered as a rollover accident for the purpose of this analysis. The independent variables would include vehicle, roadway, roadside and traffic data elements. As a minimum, the independent variables should include sideslope, vehicle type and weight, and clear zone (or recovery) distance. The independent variables can be either continuous or discreet. The resulting logistic regression equation will provide an estimate of the probability of rollover as a function of various vehicle, roadway, roadside, and traffic parameters, including sideslopes.

The average severity associated with rollover and single-vehicle, ran-off-the-road type accidents can easily be determined by compiling the injury severity data for the two accident types. Alternately, injury can be used as the dependent variable to regress against various vehicle, roadway, roadside, and traffic parameters. Again, the resulting logistic regression equations will provide estimates of the probabilities of different injury severity levels as a function of various vehicle, roadway, roadside, and traffic parameters, including sideslopes, for both rollover and single-vehicle, ran-off-the-road type accidents.

The severity for each sideslope ratio is then determined by multiplying the average injury severity or the probability of injury or severe to fatal injury associated with rollover accidents with the probability of rollover for that sideslope ratio.

## ANTICIPATED RESULTS

The anticipated results from the study are:

1. Empirical adjustment factors or revised extent of lateral encroachment curves for the various sideslopes.

2. Severity associated with various sideslopes.

## ESTIMATED COST AND TIME

| | |
|---|---|
| Estimated Cost: | \$25,000 for study on extent of lateral encroachment<br>\$50,000 for study on severity of sideslopes |
| Estimated Time: | 18 Months |

## APPENDIX D. DISTRIBUTIONS OF IMPACT CONDITIONS

### BACKGROUND

The outcome and severity of an accident involving a roadside object or feature is a function of many factors, including impact conditions (i.e., impact speed, angle, and vehicle orientation), the size and weight of the vehicle, and the nature of the roadside object or feature. In turn, the accident costs associated with the impact are determined by the accident outcome and severity. As such, the distributions of impact conditions are crucial to the accuracy and validity of the cost-effectiveness model. However, there is only limited information available on the distribution of impact conditions and the data are somewhat dated.

In a study by Perchnok, et al., on single vehicle ran-off-road fixed-object accidents on rural two-lane roadways, police officers were provided with cameras to photograph the accident scene and the involved vehicles.[22] Impact conditions were then estimated based on the photographs. Estimates of impact conditions were also obtained in a study on guardrail accidents by Lampela and Yang, again using enhanced police level accident data.[13]

In two studies by Mak, et al., indepth accident data were collected and the accidents reconstructed to estimate the impact conditions. One study involved a representative sample of accidents involving pole support structures, including utility poles, luminaries, and sign supports.[12] The other study involved single vehicle accidents at narrow bridge sites.[23] Data from these two studies were combined in an effort to develop distributions for impact speeds and angles.[24] Another potential data source is the Longitudinal Barrier Special Study (LBSS) data file, which has indepth data on over 1,000 longitudinal barrier accidents. However, these accidents were non-representative samples with bias toward the more severe accidents. This data file is being analyzed in an ongoing study and the results are not yet available. Figure 2 shows the results of the impact speed distributions from the studies by Perchnok, Lampela and Yang, and Mak. It is interesting to note the close agreement among these studies. Figure 3 shows the departure angle distributions from the same studies. Note that there is considerable discrepancy among the studies on departure angle.

Another area where there is currently very little information is the trajectory of an errant vehicle prior to leaving the roadway and after encroaching onto the roadside. For example, did the vehicle leave the roadway on the right, on the left, first right and then left, or first left and then right? Is the vehicle path straight or curved? How do the roadside conditions interact with the vehicle trajectory and the distance traveled by the vehicle prior to impact? Are the drivers braking, steering, or both? How do the driver actions affect the impact probability and impact conditions? All these vehicle trajectory parameters could potentially affect the impact probability and severity, but there are

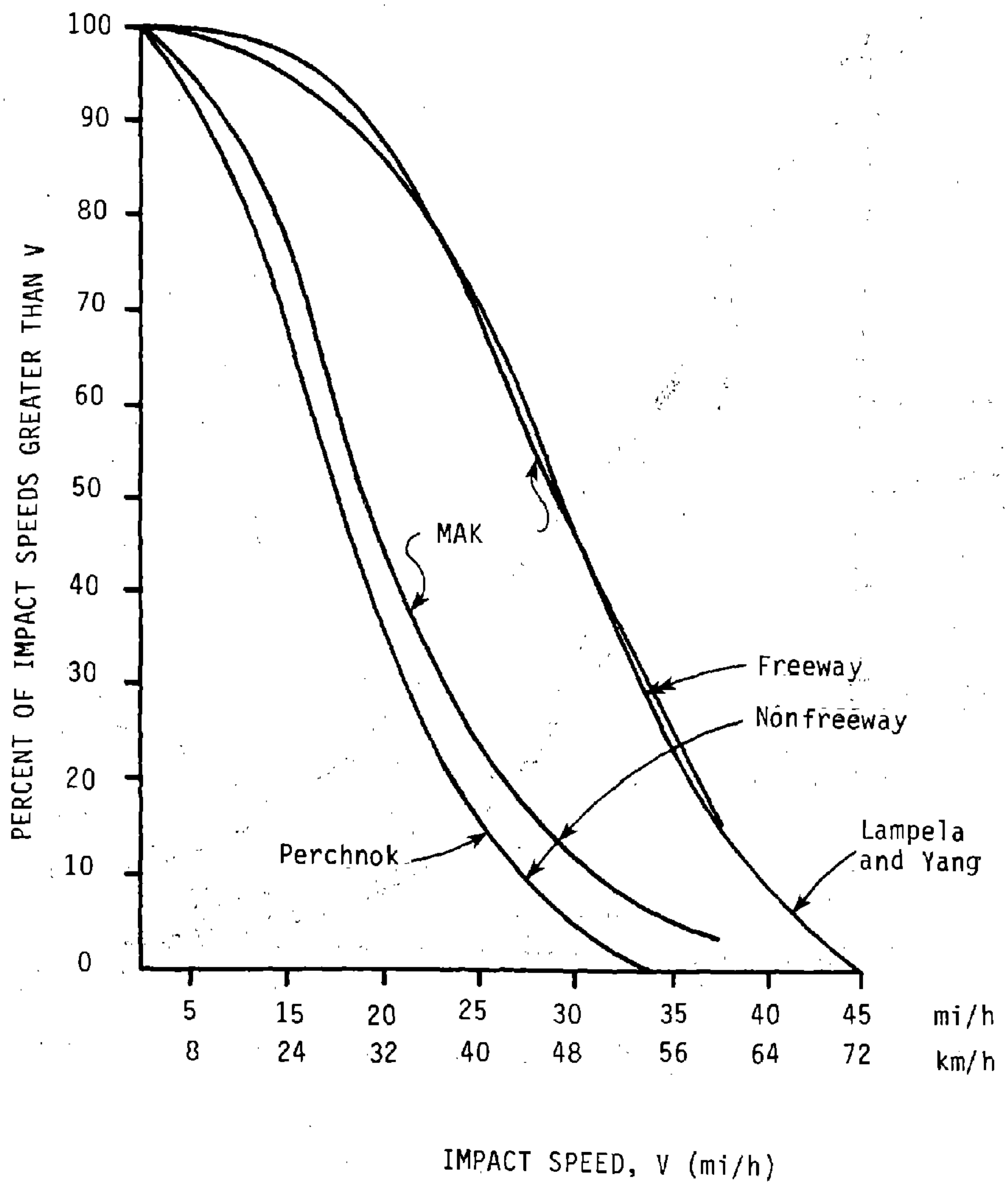


Figure 2. Impact speed distributions from accident studies.

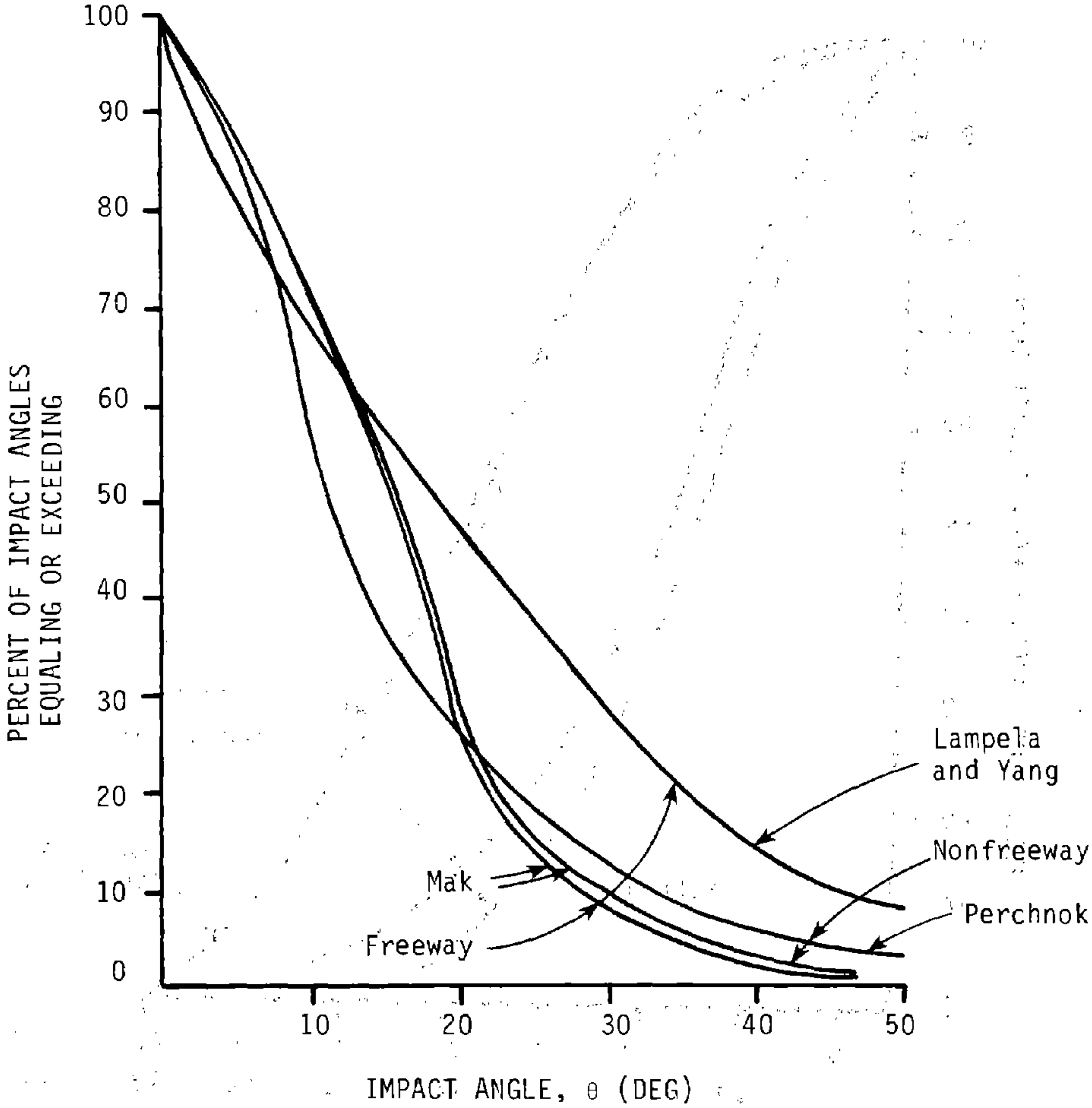


Figure 3. Impact angle distributions from accident studies.

simply insufficient data to even speculate on the answers to these questions, not to mention incorporating them into a cost-effectiveness model. Better understanding and more information on the vehicle trajectory is needed.

The BCAP program does not explicitly define the impact conditions. Instead, it defines the encroachment conditions, i.e., the speeds and angles of vehicles as they depart from the traveled portion of the roadway and the vehicle trajectory after departing from the travelway. The actual impact speeds and angles are then calculated based on the encroachment conditions and the vehicle trajectory using built-in algorithms in the BCAP program. The determination of impact conditions is an intermediate step in the estimation of accident severity and costs and users are not provided with information on the actual impact conditions. Brief descriptions of how the impact conditions are determined in the BCAP program are presented as follows.

Encroachment speed is assumed to be a function of the highway design speed (DS) with an assumed probability density function (PDF) shown in figure 4. The reference speed (RS) is defined as 90 percent of the design speed and the maximum encroachment speed is set at (RS+15) mi/h.

The maximum angle a vehicle can leave the traveled way without skidding or upsetting, assuming that the vehicle started with going straight ahead on a tangent, is determined using a point-mass model which takes into account: the offset of the vehicle from the edge of the traveled way, the initial encroachment speed of the vehicle, and the coefficient of friction. The upper limit of maximum encroachment angle is arbitrarily set at 36 degrees. The probability density function (PDF) is assumed to be triangular in shape with the greatest probability of an encroachment occurring at 0 degrees and then decreases linearly to zero at 36 degrees, as shown in figure 5A. In situations where the vehicle, because of its speed, offset, or available friction coefficient, cannot achieve the maximum 36-degree encroachment angle, the PDF is adjusted by setting the probabilities for the cells above the limiting angle to zero and readjusting the probabilities of the remaining cells to maintain an area of 1.0 under the PDF curve, as illustrated in figure 5B.

A straight line trajectory and constant deceleration rate [13 $ft/s^2$ (3.96 $m/s^2$)] beginning when the vehicle leaves the traveled way are assumed for the vehicle after encroachment. In other words, the encroaching vehicle is assumed to maintain its initial encroachment angle throughout its trajectory while the vehicle speed is assumed to diminish under the influence of braking with a constant deceleration rate. The impact speed is then calculated based on the encroachment speed, the deceleration rate, the lateral offset, and the encroachment angle. The model allows for the situations that the encroaching vehicle is braked to a stop prior to reaching the hazard or that the maximum lateral extent of an encroachment is less than the lateral offset of the hazard.

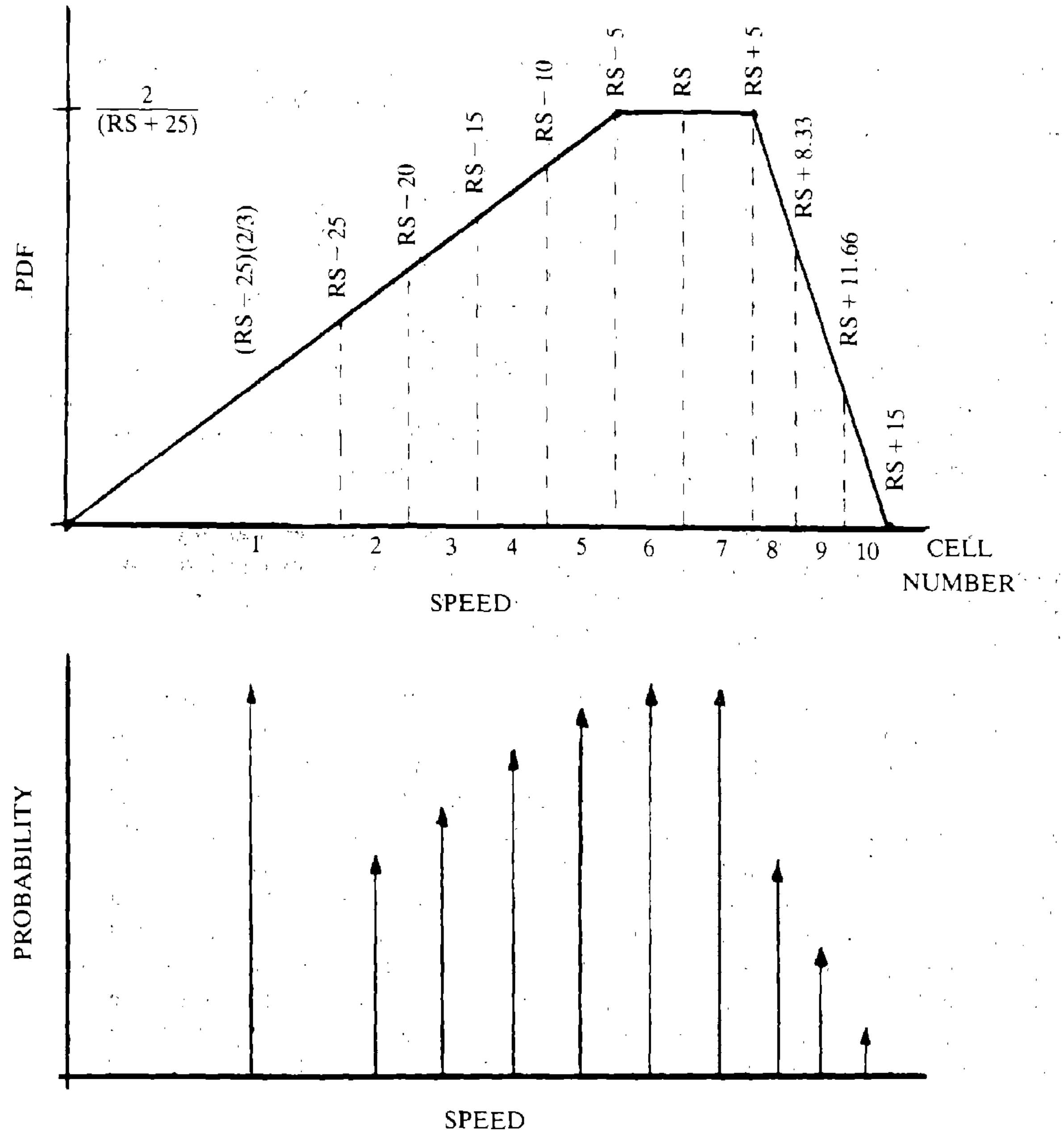


Figure 4. Encroachment speed distribution used in BCAP program.

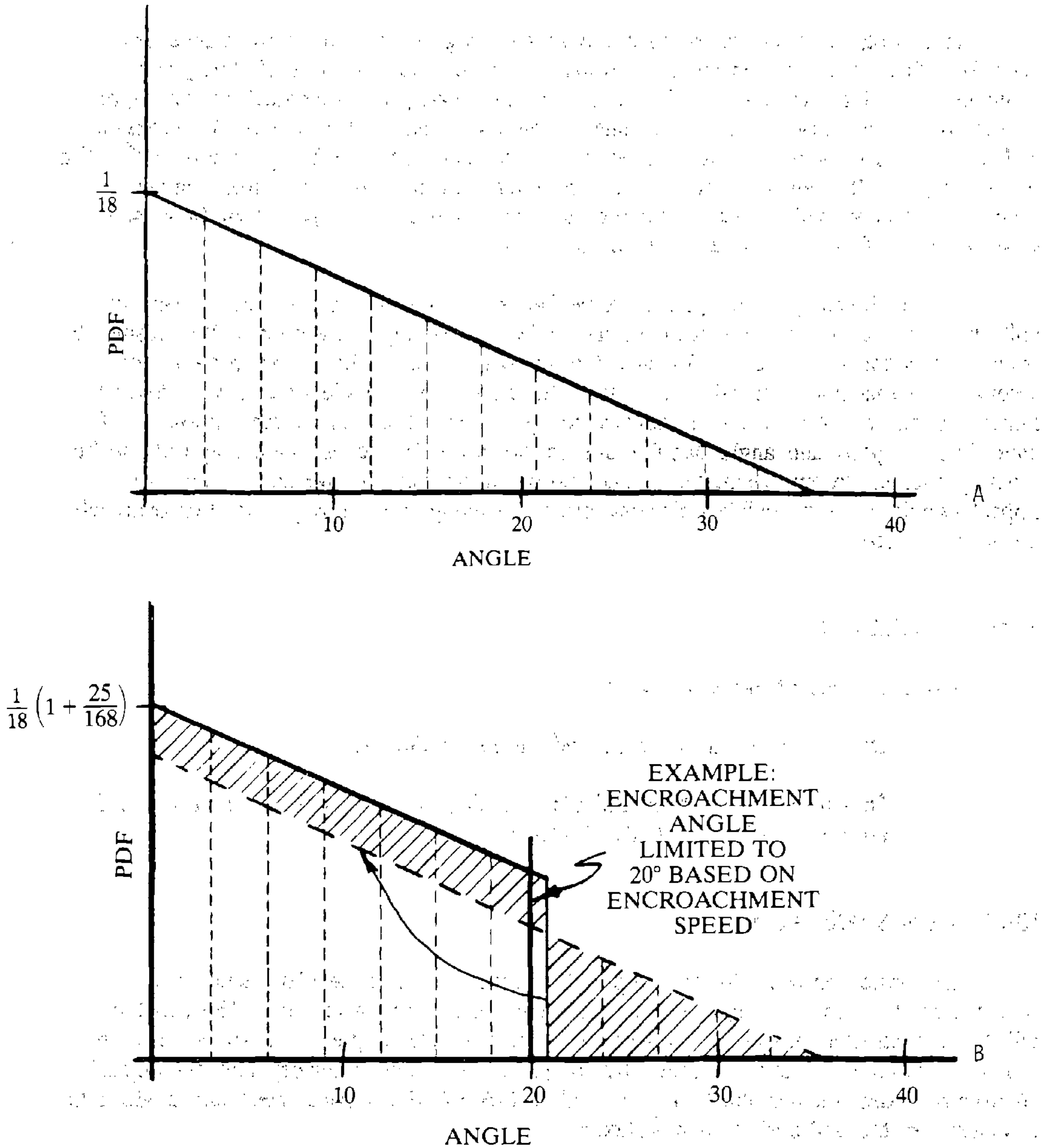


Figure 5. Encroachment angle distribution used in BCAP program.

In an ongoing study to evaluate the BCAP program and the performance level selection tables contained in the 1989 American Association of State Highway and Transportation Officials (AASHTO) *Guide Specifications for Bridge Railings*, the appropriateness and validity of the encroachment conditions assumed in the BCAP program and how they compare with the real-world impact conditions are being assessed.[1,25] The preliminary results indicate that the assumed encroachment conditions and vehicle trajectory, as contained in the BCAP program, do not produce impact conditions similar to those found from the accident studies cited above.

As mentioned previously, until some better and much less expensive means of collecting encroachment data becomes available, it is simply not economically feasible to study encroachments directly. As such, the approach used in the BCAP program of assuming encroachment speed and angle distributions and vehicle trajectory to determine impact conditions raises a lot of unanswered questions. The more direct approach of using impact speed and angle distributions in the cost-effectiveness model appears to be a better choice. In any event, better and more current data on the distributions of impact conditions and vehicle trajectory prior to leaving the roadway and after encroachment are needed.

## STUDY OBJECTIVES

The objectives of this study are to:

1. Determine the distributions of impact conditions.
2. Obtain data on vehicle trajectory, both prior to leaving the roadway and after encroaching into the roadside.

## RESEARCH APPROACH

The basic approach for the proposed study is to gather detailed data on a representative sample of single-vehicle, ran-off-the-road type accidents. The accidents will be reconstructed to obtain estimates of impact speeds, angles, and vehicle orientations. Descriptive statistics will then be compiled on vehicle trajectory and the impact conditions. Also, mathematical models will be fitted to the impact speed and angle data to determine the appropriate distributions.

The major activities for this proposed research study are as follows:

1. Select sample roadway segments for each of the six highway types, similar to that used for the base encroachment rates.

2. Set up data collection protocol, including sampling plan, accident notification scheme, data collection forms and instruction manual, and cooperation from local law enforcement agencies and vehicle repair facilities. Also, familiarize and train the investigators with the data collection protocol through a small pilot study.

3. Investigate in depth a representative sample of single-vehicle, ran-off-the-road type accidents on these selected roadway segments.

4. Reconstruct the sampled accidents to determine impact conditions.

5. Compile descriptive statistics on vehicle trajectory and impact conditions.

6. Develop mathematical models for the distributions of impact speeds and angles.

More detailed discussions on these activities are presented as follows.

**Data Requirements**

Indepth accident data will be needed for this proposed study. Police or enhanced police level accident data do not have the required level of detail to allow for reconstruction of the accidents to determine impact speeds and angles. This would require the use of trained accident investigators in the collection of the indepth accident data. As a minimum, information should be gathered on the following data items:

Roadway Cross-Sectional Data Elements.
- Number Of Lanes
- Lane Width
- Presence/Absence Of Median And Median Width
- Presence/Absence Of Paved Shoulder And Shoulder Width
- Roadside Slope
- Width Of Clear Zone

Geometric Data Elements.
- Horizontal Curvature
- Vertical Grade

Roadside Object Or Feature Struck.
- Type
- Design
- Lateral Offset
- Damage Sustained
- Performance Assessment

Vehicle Trajectory.
- Vehicle Action Prior To Leaving Roadway
- Departure Angle From Roadway
- Trajectory Of Vehicle After Leaving Roadway, But Prior To Impact

Impact Angle.

Vehicle Data Elements.
- Year; Make And Model
- Dimensions And Weight
- Damage Dimensions

Driver And Occupant Information.
- Description Of Event, Including Driver Actions
- Injury Severity

The data collection forms would be similar to those used in the National Accident Sampling System (NASS) Special Studies on longitudinal barriers, pole structures, and crash cushions.

The required sample size can be estimated using the non-parametric Kolmogorov-Smirnov test for goodness-of-fit of the observed data to the hypothesized theoretical distribution. The equation is shown as follows:

$$N = (X_a/D)^2 \qquad (7)$$

where N = Required sample size
$X_a$ = Critical statistic for level of significance $\alpha$
= 1.22 for $\alpha$ of 0.10 and 1.36 for $\alpha$ of 0.05
D = Largest of the absolute values of the N differences between the theoretical cumulative distribution function (CDF), $E(X_i)$, and the observed cumulative histogram, $O(X_i)$.

$$= \max_{i=1}^{N} |E(X_i) - O(X_i)|$$

The required sample size is a function of the level of significance, $\alpha$, and the maximum allowable difference between the theoretical and the observed cumulative distribution function, D. For example, consider a level of significance ($\alpha$) of 0.10 and a D value of 0.15, the required sample size, $N = (1.22/0.15)^2 = 66$. The corresponding sample size for a D value of 0.10 is $(1.22/0.10)^2 = 149$.

For the purpose of this study, the minimum sample size of 450 accidents, or 75 accidents for each of the six highway types, is recommended. This sample size corresponds to a level of significance ($\alpha$) of 0.10 and a D value of 0.14. It should be borne in mind that the theoretical distributions for impact speed and angle are already known from prior studies and the analysis is more one of calibration. Thus, it is believed that a relatively small sample size of 75 accidents per highway type would be adequate to provide a reasonably good approximation of the distributions. Needless to say, a larger sample size is always preferred. Also, for an accident data collection effort of this magnitude, some allowances should be made for missing data in some of the accidents which may render the accidents not useable for the analysis. The use of a larger than minimum sample size would reduce any adverse effect the missing data may have on the analysis.

**Sampling Scheme**

The same categorization scheme used with the base encroachment rates will again be used (see proposed study 1 in appendix A for details). It is anticipated that the following six highway types will be used for the base encroachment rates:

- Rural Interstates and Freeways.
- Rural Multilane Undivided Highways.
- Rural Two-Lane Highways.
- Urban Interstates and Freeways.
- Urban Multilane Undivided Highways.
- Urban Two-Lane Highways.

In other words, since a different base encroachment rate will be developed for each of these six highway types, it is logical that different impact speed and angle distributions will be developed for each of the six highway types.

For each of the six highway types, typical roadway segments will be selected for inclusion in the study. Every effort should be made to select roadway segments that are typical or representative of the respective highway type. Roadway segments with unusual characteristics should be excluded. A more rigid set of selection criteria to select roadway segments that are statistically "representative" is probably not practical since the locale where these roadway segments are to be selected will be mostly a function of the contractor(s) conducting the study. However, it would be desirable, if possible, to collect the accident data from more than one geographical locations so that the data may be somewhat more representative.

For the selected roadway segments, a representative sample of single vehicle accidents involving roadside objects and features will be selected for indepth investigation. The sampling plan could vary from something very simple, such as investigating every single-vehicle, ran-off-the-road accident that occurred on the selected roadway segments, to something more elaborate, such as a stratified random sampling scheme wherein certain accident types are over-sampled for better data distribution and analysis results. The design of the sampling plan needs to take into account many factors, some of which are discussed as follows.

In previous efforts to define impact speed and angle distributions, it was found that the greatest variations are typically associated with the high end of the distributions because of the scarcity of data. Over-sampling of accidents with high impact speeds and/or impact angles would reduce the variability in the data and provide better fit for the distributions. However, since impact conditions are not known at the time of sampling, a surrogate measure will have to be used. It can be argued that accidents with higher injury severity are generally associated with more severe impact conditions and are therefore good surrogate measures. Thus, it is recommended that accidents with severe to fatal (A + K) injuries be over-sampled in the sampling scheme. Furthermore, the results of cost-effectiveness models are typically driven by the more severe accidents, which adds to the importance of better accuracy with the high end of the impact condition distributions.

The sampling rates used overall or for the individual strata (if over-sampling of more severe accidents is included) are a function of the available number of single-vehicle, ran-off-the-road type accidents, i.e., the accident population, and the desired work load, i.e., number of accidents to be investigated per week. Note that the accident population is in turn dependent on the number and length of roadway segments selected for study. A typical sampling scheme that has been shown to work well is to select accidents based on certain numbers or letters from the last digit or letter of the license plates of the vehicles involved in the accidents.

A typical accident notification system is through review of police accident reports on a periodic basis. Arrangements are made with local law enforcement agencies to provide copies of accident reports on eligible accidents, e.g., all single vehicle accidents occurring on the selected roadway segments. The accident reports will then be reviewed and those meeting the sampling criteria will be selected for indepth investigation. The frequency of obtaining and reviewing the accident reports should be a minimum of two times a week, and preferably more, to keep the time lag from occurrence of an accident to the time of investigation to no more than 3 or 4 days. Longer time lags could lead to significant increases in the extent of unknown or unobtainable data.

**Accident Investigation and Reconstruction**

Each sampled accident will be investigated in depth by trained accident investigators. The investigation will include, as a minimum, inspection and documentation of the accident site and the involved vehicle with comprehensive photographic coverage. A brief telephone interview with the involved driver is desirable, but not required.

The completed data collection forms will be quality controlled to assure completeness and accuracy of the coded data which will then be entered into a data base. A scaled diagram of the accident will be prepared as part of the case file. Each sampled accident will then be reconstructed to the extent possible to estimate the impact speed. It is anticipated that a variety of reconstruction tools, from manual procedures to computer simulation models, will be needed for the reconstruction. A single standardized reconstruction procedure that can be used with all the accidents would be ideal, but not practical given the wide variety of roadside objects and features and impact configurations. For those accidents where detailed reconstruction is not possible due to missing or unknown data, the impact speed will be estimated, if possible, in gross speed ranges, e.g., 0-20, 20-40, 40-60, and 60+ mi/h (0-32.2, 32.2-64.4, 64.4-96.6, 96.6+ km/h). It is evident that the expertise and experience of the person(s) conducting the reconstruction will be crucial to the accuracy and validity of the reconstruction effort.

**Analytical Procedure**

Descriptive statistics on the vehicle trajectory and impact conditions of the sampled accidents will first be compiled for information. Note that the data will have to be weighted to account for the sampling rate or rates, particularly if the more severe accidents are over-sampled as recommended.

Mathematical models will be fitted to the data to establish the distributions of impact speeds and angles. It has been found in previous studies that the gamma distribution provides a good fit for the univariate impact speed and angle distributions. However, it presents a problem when a joint distribution for impact speed and angle is required since there is no bivariate gamma distribution. The logistic normal distribution may be a better alternative if it fits the data. The advantage of the logistic normal distribution is that, with appropriate transformations, a bivariate normal distribution may be developed for the joint distribution of the impact speed and the impact angle. A weighted least-square-error regression model is probably the easiest way to fit the data to the theoretical distributions. The resulting distributions will then be tested for the goodness-of-fit to check how well the theoretical models agree with the accident data.

Note that the analysis will be repeated for each of the six highway types, i.e., impact speed and angle distributions will be developed for each highway type and the associated base encroachment rate.

## ANTICIPATED RESULTS

The anticipated results from the study are:

1. Impact speed and angle distributions for each highway type and associated base encroachment rate.

2. Better understanding and more information on vehicle trajectory prior to leaving the roadway and after encroaching into the roadside. The findings could possibly lead to improvements in the cost-effectiveness model by incorporating vehicle trajectory into the model.

## ESTIMATED COST AND TIME

Estimated Cost: $625,000

Estimated Time: 36 Months

The cost breakdown includes $50,000 for initial setup of the data collection protocol and the pilot study, $450,000 for the actual data collection effort (450 accidents at $1,000 per accident), $100,000 for reconstruction of the accidents and development of the data base, and $25,000 for analysis and report preparation.

## APPENDIX E. RELATIONSHIPS OF IMPACT CONDITIONS, PERFORMANCE LIMITS, AND INJURY PROBABILITY AND SEVERITY

### BACKGROUND

The outcome and severity of an impact with a roadside object or feature is a function of many factors, including impact conditions (i.e., impact speed, angle, and vehicle orientation), the size and weight of the errant vehicle, and the nature of the impacted roadside object or feature. The distributions of the impact conditions are addressed under proposed study 4 in appendix D. This proposed study will examine the relationships of impact conditions to the performance limits of various roadside safety devices and features, and to the resulting injury severity.

The performance limit of an impacted roadside object or feature is an important factor to the severity of an impact. When the performance limit is exceeded, e.g., loading is greater than barrier capacity, some catastrophic outcome could occur, such as penetration of the barrier or rolling over the barrier by the impacting vehicle. Under such circumstances, the severity of the impact is usually a function of the catastrophic outcome. For situations where the performance limit is not exceeded, e.g., redirection for a barrier, severity is a function of the impact conditions. Currently, the performance limits of roadside objects and features and the potential outcomes of exceeding the performance limits are not well defined, nor are the relationships between impact conditions and impact severity.

Impact Severity is ideally expressed in terms of injury probability and severity. However, due to lack of data, severity is often expressed in terms of surrogate measures. For example, the BCAP program uses a severity index with an 11-point (0-10) scale to describe the impact severity. For catastrophic failures where the performance limits were exceeded, i.e., penetrations and rolling over the bridge railings, a fixed severity index was assigned to the impact severity, e.g., severity index of 7.0. For redirectional impacts, the severity is defined as a linear function of the lateral acceleration experienced by the impacting vehicle.

This 11-point severity index scale was first developed for the 1977 AASHTO Barrier Guide, primarily on the basis of engineering judgement with very limited supporting data.[3] The severity index scale is defined in terms of percentages of property-damage only (PDO), injury, and fatal accidents for each level of the scale. Severity indices associated with various roadside objects and features were also established under the 1977 AASHTO Barrier Guide based on estimates provided by highway and design engineers in a survey. It is believed that these estimates were based on the presumption of high-speed impacts [60 mi/h (96.6 km/h)] impacts and are thus overestimated in terms of severity. While the BCAP program modified these severity indices and incorporated some linear relationships between impact conditions and impact severity, there remain a lot of unanswered questions regarding these severity indices and assumed relationships.

In crash testing, severity is currently defined in terms of occupant impact velocity and highest 10-ms average ridedown acceleration.[26] The 50-ms highest average acceleration was used previously to define severity.[27] The relationships of these surrogate severity measures to injury probability and severity are not well established. In fact, efforts to relate these surrogate severity measures to actual injury probability and severity from real-world accident data have not been successful.[28,29] However, it is believed that the failure of these studies to establish these relationships is the result of the research methodology and that such relationships could be established with a proper research approach.

In order to better predict the expected severity of an impact, it is necessary to have more information and better understanding on the performance limits of various roadside objects and features, the potential outcomes of exceeding these performance limits, and the relationships between impact conditions, performance limits, and injury probability and severity. Also, it would be desirable to either improve on and validate the existing severity indices or to develop a revised set of severity indices that better reflects the impact severity and can be incorporated into the cost-effectiveness models.

## STUDY OBJECTIVES

The primary objectives of this study are to:

1. Determine the performance limits of various roadside objects and features and the potential outcomes of exceeding the performance limits and the associated severity.

2. Relate injury probability and severity to impact conditions.

In addition, there are two secondary objectives to:

1. Improve on and validate existing severity indices or develop new severity indices that better reflect injury probability and severity.

2. Relate surrogate severity measures used in full-scale crash testing and simulation to actual injury probability and severity.

## RESEARCH APPROACH

There are four distinct and separate analyses under this research study, one for each of the primary and secondary objectives. Each analysis can actually be conducted as a separate study, independent of the other three analyses. Thus, discussions on the general research approach will be presented as if they are four separate studies.

The first study is to determine the performance limits of various roadside objects and features and the potential outcomes of exceeding the performance limits and the associated severity. For each roadside object or feature to be studied, a sample (not necessarily representative) of accidents involving failures of that specific roadside object or feature, e.g., penetration or rolling over a barrier, will be investigated in depth. The sampled accidents will be reconstructed to estimate the impact conditions. The data can then be used to define the envelope of performance limit for that specific roadside object or feature. A validation check is available by comparing the envelope of performance limit to the impact conditions of accidents involving that specific roadside object or feature which did not result in failure from the second study presented below. Another potential validation check that is beyond the scope of this study is to conduct full-scale crash tests on one or more points of the performance limit envelope to determine how well the predicted performance limit envelope agrees with actual crash test results.

The second study is to determine the relationships between injury probability and severity and impact conditions for various roadside objects and features. Again, for each roadside object or feature to be studied, a sample (not necessarily representative) of accidents involving that specific roadside object or feature which did not result in failure will be investigated in depth. The sampled accidents will be reconstructed to estimate the impact conditions. The data can then be analyzed to define the relationships between impact conditions and injury probability and severity for that specific roadside object or feature.

The third study is to develop better severity indices that accurately reflect injury probability and severity and are easy to use for modelling purposes. This can be accomplished by either improving and validating existing severity indices or developing new severity indices. It is difficult to define the research approach for this study since it is not a set procedure that can be prescribed in a step-by-step manner. The researcher(s) will basically examine the results from the first two studies to make an assessment as to how well the existing severity indices, such as those used with the BCAP and ROADSIDE program, agree with the injury probability and severity observed from the accident data. This could lead to revision or improvement to the existing severity indices or development of entirely new severity indices. It may even be found that it is just as easy to use injury probability and severity directly in the model without resorting to the use of severity indices.

The fourth study is to establish relationships between surrogate severity measures used in full-scale crash testing and simulation studies (i.e., highest 50-ms average acceleration, occupant impact velocity, and highest average 10-ms ridedown acceleration) and actual injury probability and severity. As mentioned previously, past efforts to establish such relationships have not been successful due to flaws in the research methodology. In one study, a mathematical severity index, defined as the result of the reported maximum 50-ms vehicle longitudinal and lateral accelerations, was calculated for a sample of full-scale crash tests and compared to an accident severity index, predicted as a function of vehicle type or weight, impact speed, and impact angle.[28] Another recently completed study attempted to establish such relationships using the police vehicle damage scale (TAD) as the common link between full-scale crash tests and real-world accidents.[29] The major problem with both attempts is the reliance on full-scale crash test data that are limited to basically one impact speed [60 mi/h (96.6 km/h)], three impact angles (15, 20, and 25 degrees), and two vehicle weight categories [1,800 and 4,500 lb (817 and 2,043 kg)]. The study using the TAD scale further suffers from the lack of precision associated with the TAD scale, which is an ordinal scale of 1 to 7 with a precision of no better than Ý1. This lack of variability and precision in the data greatly diminish any chance of establishing any meaningful relationships.

A different research approach is proposed for this study, which hopefully will have a better chance of success. A representative sample of indepth accident cases with known injury severity will be reconstructed using available simulation models, such as SMAC, BARRIER VII, HVOSM, and NARD. These simulation programs provide an estimate of the impact conditions as well as the acceleration history experienced by the vehicles. The surrogate severity measures, such as occupant impact velocity and ridedown acceleration, can then be determined from the acceleration history and compared with the injury severity. Relationships, if any, between the surrogate severity measures and actual injury probability and severity from the accidents will be developed. This proposed research approach effectively eliminates the problems posed by the lack of variability associated with the use of full-scale crash test data.

The major activities for this proposed research study are as follows:

1. Select specific roadside object(s) and/or feature(s) for study.

2. Set up data collection protocol, including sampling plan, accident notification scheme, data collection forms and instruction manual, and cooperation from local law enforcement agencies and vehicle repair facilities. Also, familiarize and train the investigators with the data collection protocol through a small pilot study.

3. Investigate in depth a sample of single-vehicle accidents involving the specific roadside object(s) and/or feature(s) under evaluation.

4. Reconstruct the sampled accidents to determine impact speeds and angles.

5. Analyze data on accidents in which the performance limits are exceeded to define the performance limits and the associated injury probability and severity for the roadside object(s) and/or feature(s) under evaluation.

6. Analyze data on accidents in which the performance limits are not exceeded to establish relationships between injury probability and severity and impact conditions for the roadside object(s) and/or feature(s) under evaluation.

7. Examine the accident data to determine if severity indices that better reflect injury probability and severity can be developed.

8. Use computer simulation to estimate surrogate severity measures used in full-scale crash testing and simulation for a selected sample of accidents. Establish relationships, if any, between the surrogate severity measures and actual injury probability and severity observed from accident data.

More detailed discussions on these activities are presented as follows.

**Data Requirements**

Similar to Proposed Study 4 on the distributions of impact conditions (see appendix D), indepth accident data will be needed for this proposed study. Police or enhanced police-level accident data do not have the required level of detail to allow for reconstruction of the accidents to determine impact speeds and angles. This would require the use of trained accident investigators in the collection of the indepth accident data.

The data requirements and the associated data collection forms for this study will be similar to those for proposed study 4, which include, as a minimum, the following data items:

Roadway Cross-Sectional Data Elements.
- Number Of Lanes
- Lane Width
- Presence/Absence Of Median And Median Width
- Presence/Absence Of Paved Shoulder And Shoulder Width
- Roadside Slope
- Width Of Clear Zone

Geometric Data Elements.
- Horizontal Curvature

Vertical Grade
Roadside Object Or Feature Struck.
Type
Design
Lateral Offset
Damage Sustained
Performance Assessment
Vehicle Trajectory.
Vehicle Action Prior To Leaving Roadway
Departure Angle From Roadway
Trajectory Of Vehicle After Leaving Roadway, But Prior To Impact
Impact Angle.
Vehicle Data Elements.
Year, Make And Model
Dimensions And Weight
Damage Dimensions
Driver And Occupant Information.
Description Of Event, Including Driver Actions
Injury Severity

It should be noted that the estimates of sample sizes provided below are for each roadside object or feature under evaluation. In other words, the total number of accidents to be investigated would be the product of the sample size required for each roadside object or feature times the number of roadside object(s) and/or feature(s) selected for evaluation.

To estimate the required sample size, the following equation may be used:

$$N = Z^2_{\alpha/2}(p_i q_i)/\epsilon^2 \qquad (8)$$

where
- $N$ = Required sample size
- $Z$ = Normalized value
- $\alpha$ = Level of significance
- $p_i$ = Estimated proportion of injury for severity i
- $q_i$ = 1 - $p_i$
- $\epsilon$ = Precision, i.e., difference to be detected

To illustrate the application of this equation, consider the following example with the level of significance, $\alpha$, at 0.10, an estimated proportion of injury ($p_i$) of 30 percent, and a desired precision ($\epsilon$) of 10 percent. The required sample size, N, is:

$$
\begin{aligned}
N &= (Z_{0.05})^2(0.30 \times 0.70)/(0.10)^2 \\
&= (1.64)^2(0.21)/0.01 \\
&= 56
\end{aligned} \tag{9}
$$

An alternate method of specifying the sample size is to simply select a fixed number of accidents to be investigated for each roadside object or feature. The minimum sample size recommended for each roadside object or feature under evaluation is 300 accidents, 75 of which involved failures, 125 with resulting severe to fatal injuries and 100 with no to moderate injuries. Again, a larger sample size is preferred to allow for accident cases with missing data. More detailed discussion on the sampling scheme is presented in the following section.

Note that the required accident data for some of the roadside objects and features may already be available. For example, the Longitudinal Barrier Special Study (LBSS) data file could be used for guardrail and median barrier accidents, the narrow bridge study data for bridge railings, and the pole study data for utility poles and breakaway and non-breakaway luminaires.[12,23] Also, accident data collected in proposed study 4 to determine distributions of impact conditions (see appendix D) will also be applicable for use in this study.

**Sampling Scheme**

Unlike the sampling scheme for proposed study 4 to determine the distribution of impact conditions, the types of analyses to be conducted under this study do not necessarily require a representative sample. For the study on performance limits, one would examine only those accidents involving failures of the specific roadside object or feature under evaluation and not a representative sample. Similarly, for the study on relationships between injury probability and severity and impact conditions, the emphasis for the sampling scheme is to make sure that adequate sample sizes are available throughout the entire spectrum of impact conditions and not representativeness of the data itself. While it is not necessary to have a representative sample, it would be desirable, if possible, to collect the accident data from more than one geographical location so that the data may be somewhat more representative.

A stratified random sampling scheme would probably work best for this study by allowing for over-sampling of certain accident types to provide better data distribution and analysis results. For each roadside object or feature under study, a minimum of three strata are anticipated:

1. Accidents involving failures of the roadside object or feature.

2. Accidents not involving failures of the roadside object or feature, but resulting in severe to fatal injuries, i.e., A or K injuries.

3. Accidents not involving failures of the roadside object or feature, but resulting in no to moderate injuries, i.e., property damage only or C or B injuries.

The first stratum involving failure of the roadside object or feature under study is intended for use with defining the performance limits and the associated injury probability and severity. Note that, for some roadside objects and features, the failures are not necessarily evident from the police accident reports, e.g., the failure of a breakaway luminarie to properly break away upon impact. For such roadside objects and features, it would not be possible to specifically sample for accidents involving failures. The alternative is to increase the sample size for the more severe accidents, on the assumption that accidents involving failures of the roadside object or feature are likely to result in more severe injuries.

The second and third strata are intended for over-sampling of the more severe accidents. In previous efforts to determine relationships between injury probability and severity and impact conditions, it was found that the greatest variations are typically associated with the high end of the impact conditions and injury severity because of the scarcity of data. It can be argued that more severe accidents are generally associated with more severe impact conditions. Thus, over-sampling of the more severe accidents would provide more data on the high end of the spectrum, resulting in less variability in the data and hopefully better fit for the mathematical models.

The sampling rates used for the individual strata are a function of the available number of accidents involving the specific roadside object or feature under study, i.e., the accident population, and the desired work load, i.e., number of accidents to be investigated per week. The accident population is in turn a function of the frequency of installations for that specific roadside object or feature and the geographical area or the number of miles of highways covered in the study. However, it is expected that a 100-percent sampling will be necessary for accidents involving failures due to the rare nature of such occurrences. For the other two strata where sampling is likely required, a typical sampling scheme that has been shown to work well is to select accidents based on certain numbers or letters from the last digit or letter of the license plates of the vehicles involved in the accidents.

A typical accident notification system is through review of police accident reports on a periodic basis. Arrangements are made with local law enforcement agencies to provide copies of accident reports on eligible accidents, e.g., all single vehicle accidents involving the specific roadside object(s) and/or feature(s) under study. The accident reports will then be reviewed and those meeting the sampling criteria will be selected for indepth investigation. The frequency of obtaining and reviewing the accident reports should be a minimum of two times a week, and preferably more, to keep the time lag from occurrence of an accident to the time of investigation to no more than 3 or 4 days. Longer time lags could lead to significant increases in the extent of unknown or unobtainable data.

### Accident Investigation and Reconstruction

Each sampled accident will be investigated in depth by trained accident investigators. The investigation will include, as a minimum, inspection and documentation of the accident site and the involved vehicle with comprehensive photographic coverage. A brief telephone interview with the involved driver is desirable, but not required.

The completed data collection forms will be quality controlled to ensure completeness and accuracy of the coded data which will then be entered into a data base. A scaled diagram of the accident will be prepared as part of the case file. Each sampled accident will then be reconstructed to the extent possible to estimate the impact speed. It is anticipated that, for each roadside object or feature, a single standardized reconstruction procedure will be used. However, the reconstruction procedure will likely be different for different roadside objects and features. For those accidents where detailed reconstruction is not possible due to missing or unknown data, the impact speeds will be estimated, if possible, in gross speed ranges, e.g., 0-20, 20-40, 40-60, and 60+ mi/h (0-32.2, 32.2-64.4, 64.4-96.6, and 96.6+ km/h), based on available data. An experienced accident reconstructionist can provide reasonably good gross impact speed estimates even with partial data, such as photographs of the damaged vehicle and roadside object or feature.

### Analytical Procedure

For the study on performance limits, the analysis approach involves first the selection of a measure (or measures) that best defines the impact severity for the specific roadside object or feature under evaluation. For example, the severity of a barrier impact may be defined by the lateral component of the kinetic energy of the impact vehicle, which takes into account the impact speed, impact angle, and weight of the impacting vehicle. For a point object, such as a breakaway luminarie or sign support, the impact severity measures may be momentum or kinetic energy, which takes into account the impact speed and weight of the vehicle, and impact configuration, which includes vehicle orientation and point of impact, e.g., front, side or rear of vehicle.

For each of the investigated accidents involving failures of the specific roadside object or feature, the value of the selected impact severity measure(s) will be determined and tabulated or plotted. The performance limit will then be determined based on the lower bound of the values of the impact severity measure(s). The determination of the injury probability and severity associated with exceeding the performance limit is simply a matter of compiling the injury severity data on these accidents involving failures.

The performance limit should be checked by comparing the performance limit to the upper bound values of the impact severity measure(s) for accidents involving the same roadside object or feature, but did not result in failures. In other words, the impact severity measure(s) for accidents not resulting in failure of the roadside object or feature should generally be lower than the performance limit. Another potential validation check is to conduct full-scale crash tests on one or more points of the performance limit envelope to determine how well the predicted performance limit envelope agrees with actual crash test results. Although this validation check is beyond the scope of this study, it is felt that such crash tests would better define the performance limits of existing roadside safety appurtenances and be highly desirable. These crash tests are, therefore, recommended for consideration.

Similarly, for the study on relationships between injury probability and severity and impact conditions, a measure (or measures) that best defines the impact severity for the specific roadside object or feature under evaluation will first be selected, which should be the same as that used for the study on defining performance limits. For each of the investigated accidents not involving failures of the specific roadside object or feature, the value of the selected impact severity measure(s) will be determined and tabulated or plotted against the injury severity for that accident. Mathematical models will be fitted to the data to establish the relationships between the impact severity measure(s) and injury severity. It has been found in previous studies that sigmoid curves appear to provide good fit for the probability of injury. A least-square-error regression model is probably the easiest way to fit the data to the mathematical models. The resulting models will then be tested for goodness-of-fit to check how well the models agree with the accident data.

An alternate analysis approach is to use the standard logistic regression procedure in which injury severity is the dependent variable. The independent variables could be parameters associated with impact conditions, e.g., impact speed, impact angle, impact configuration, vehicle weight, etc., or the impact severity measure(s) as described above. Also, the independent variables can be either continuous or discreet.

It is anticipated that three sets of logistic regression equations will be developed for each of the roadside object(s) and/or feature(s) under study to relate the effects of impact conditions to:

1. Probability of failure.

2. Probability of injury severity given a failure.

3. Probability of injury severity given not a failure.

The analysis will be repeated for each of the roadside object or features selected for evaluation in the study.

A note of caution that should be borne in mind when analyzing the probability of injury severity is the potential effect of unreported accidents. For most roadside objects and features, it is reasonable to assume that impacts that did not result in reported accidents are typical low in impact and injury severity since the driver managed to remove the vehicle from the scene. Thus, unreported accidents do not really pose any problem to the analysis relating impact conditions to the probability of injury. However, for some roadside safety devices, such as crash cushions and guardrail end treatments, the assumption that unreported accidents are necessarily low in impact severity is no longer valid. These roadside safety devices perform so well that drivers still managed to remove the vehicles from the scene even under severe impact conditions. As such, the reported accidents involving these roadside safety devices tend to be more severe in nature and are not truly reflective of the relationships between impact conditions and injury severity. In fact, the analysis may erroneously indicate that these roadside safety devices are not performing well due to the high resulting injury severity of reported accidents while exactly the opposite is true when the unreported accidents are taken into account.

As mentioned previously, it is difficult to define the analytical approach for the study to develop better severity indices since it is not a set procedure that can be prescribed in a step-by-step manner. The basic approach is to examine the results from the first two studies on the relationships among impact conditions, performance limits, and injury probability and severity, to make an assessment as to how well the existing severity indices, such as those used with the BCAP and ROADSIDE program, agree with the injury probability and severity observed from the accident data. Consideration will then be given to revision or improvement of the existing severity indices or development of entirely new severity indices.

For the study to establish relationships between surrogate severity measures used in full-scale crash testing and simulation studies and injury probability and severity, a representative number of indepth accident cases will be reconstructed using available simulation models, such as SMAC, BARRIER VII, HVOSM, and NARD, to obtain estimates of the surrogate severity measures. Relationships, if any, between the surrogate severity measures and actual injury probability and severity from the accidents will be developed. Note that this analysis is not confined to any specific roadside object or feature since these surrogate severity measures apply to the evaluation of crash test results for all roadside objects and features.

## ANTICIPATED RESULTS

The anticipated results from the study are:

1. Better prediction of the expected severity of an impact with various roadside objects and features.

2. Better understanding on the performance limits and the relationships between impact conditions, performance limits, and injury probability and severity for various roadside objects and features.

3. Better understanding and more information on severity indices. The findings could lead to improvement of existing severity indices or development of new severity indices that would better reflect injury probability and severity.

4. Relationships, if any, between surrogate severity measures used in full-scale crash testing and computer simulations to actual injury probability and severity.

## ESTIMATED COST AND TIME

Estimated Cost: $450,000* for the first roadside object or feature
$400,000** for each subsequent roadside object or feature
$25,000 for study on severity indices
$50,000 for study on surrogate severity measures

* The cost breakdown for the first roadside object or feature includes $50,000 for initial setup of the data collection protocol and the pilot study, $300,000 for the actual data collection effort (300 accidents at $1,000 per accident), $75,000 for reconstruction of the accidents and development of the data base, and $25,000 for analysis and report preparation.

** The cost breakdown for each subsequent roadside object or feature includes $10,000 for initial setup of the data collection protocol and the pilot study, $300,000 for the actual data collection effort (300 accidents at $1,000 per accident), $75,000 for reconstruction of the accidents and development of the data base, and $15,000 for analysis and report preparation.

Estimated Time: Various, depending on number of roadside objects and/or features studied. Range - 30 to 48 months.

# APPENDIX F. COMBINED PROPOSED STUDIES 1 AND 2 VALIDATION OF ENCROACHMENT FREQUENCY/RATE

## BACKGROUND

One of the major comments from the expert panel and the FHWA is that it may be desirable to incorporate proposed study 2, "Determination of Encroachment Frequency/Rate Adjustment Factors" as part of proposed study 1, "Validation of Encroachment Frequency/Rate." Concern was expressed over the appropriateness of using single-vehicle, ran-off-road accident rates as a surrogate measure for encroachment rates in determining the adjustment factors. Also, it was felt that the research approach as proposed for validation of the encroachment frequency/rate in proposed study 1 (see appendix A) is a better and more direct means to determine the encroachment frequencies/rates for various combinations of highway types and selected geometric and roadway characteristics without the additional step of using empirical adjustment factors.

The rationale behind the original proposed plan of conducting two separate studies, one to validate the encroachment frequency/rate (proposed study 1) and a second to develop empirical adjustment factors for various geometric and roadway characteristics, is briefly explained as follows: It is recognized that encroachment rates are related to a number of parameters, such as highway type, traffic volume, horizontal curvature, vertical grade, number of lanes, lane width, shoulder width, etc. Proper evaluation of the effects of all of these parameters on encroachment frequency or rate would require an enormous data collection effort and would be prohibitively expensive. On the other hand, a single encroachment rate for all highway types and situations is clearly inappropriate. A compromise is therefore proposed to develop separate base or average encroachment rates for six different highway types. It is reasoned that the highway type will serve as a surrogate measure for all the other parameters that could potentially affect encroachment frequency or rate.

Also, it is believed that the effects of the other parameters on encroachment frequency/rate can be evaluated with a totally different research methodology that can accommodate a large number of factors without the expenses associated with the field monitoring effort. The proposed research methodology is the use of single-vehicle, ran-off-the-road accidents as a surrogate measure for encroachments, thus allowing the use of reported police accident data that are readily available. The effects of the various geometric and roadway characteristics on encroachment frequency/rate can then be expressed in terms of empirical adjustment factors.

In light of the expressed preference by the expert panel and the FHWA to consider combining the two proposed studies 1 and 2 into a single study, a data collection plan for the combined study is developed and presented in this appendix.

## STUDY OBJECTIVES

The primary objective of this combined study is essentially the same as that for proposed study 1, which is to validate and adjust the encroachment rates used in encroachment probability-based cost-effectiveness models. A secondary objective is to determine the extent of unreported accidents for various roadside objects.

## RESEARCH APPROACH

The general approach for the proposed combined study is similar to that for proposed study 1 (see appendix A). Again, there are two alternate approaches to the conduct of this study:

1. Review reported accidents for selected roadside objects.

2. Monitor selected roadside objects for impact damage.

Details of these two alternate research approaches, with the exception of the sampling scheme, are similar to those for proposed study 1 (see appendix A), and discussions of these two alternate approaches will not be repeated herein. The readers are referred to proposed study 1 in appendix A for details of these activities. Brief discussions on the revised sampling scheme are presented as follows.

### Sampling Scheme

The sampling scheme for the combined study will include the six highway types, as discussed under proposed study 1 and selected geometric and roadway characteristics considered to have significant effects on the encroachment frequency/rate. The specific geometric and roadway characteristics for inclusion into the sampling scheme will have to be pre-selected. Note that it may not be possible to evaluate the effect of other parameters not included in the sampling scheme. To properly select the geometric and roadway characteristics to be included in the sampling scheme, it is necessary to have sufficient prior knowledge of the effects of various parameters on encroachment frequencies/rates.

While there have been a number of studies conducted to examine the effects of various geometric and roadway characteristics on accident rates, such as horizontal and vertical alignment, cross-sectional elements, etc., the state of the knowledge in this area is still very limited. In a study conducted by the Transportation Research Board (TRB) and reported in TRB Special Report 214, *Designing Safer Roads - Practices for Resurfacing, Restoration, and Rehabilitation*, many of these previous studies were critically reviewed.[14] The study concludes that "...notenough is known about the safety gains that will occur after the geometry of existing highways is improved or other safety-oriented improvements are made...past studies of the safety effects of geometric design improvements frequently lacked rigorous statistical control, a shortcoming that severely limits the accuracy of study results."

Another important point to be borne in mind in setting up the sampling scheme is the number of parameters that can be included and the associated sample size required. As discussed previously under proposed study 1, the recommended sample size is 75 expected encroachments for each of the six highway types, or a total of 450 expected encroachments. The required sample size will increase geometrically as additional parameters are added to the sampling scheme. For example, if horizontal curvature with six levels (e.g., outside versus inside of curves, and $<= 3°$, $3°$ to $6°$, and $>= 6°$) are added to the six highway types, the number of combinations is increased from 6 to 36 (6 highway types x 6 horizontal curvatures) and the total required sample size would accordingly be increased sixfold from 450 to 2,700 expected encroachments. It is evident from the above illustration that the number of parameters and the levels within each parameter that can be added to the sampling scheme are very limited before the required sample size would become economically prohibitive.

With the above discussions in mind, the setup of the sampling scheme is simply a matter of selecting the specific geometric and roadway characteristics to be included while taking into account the sample size attainable with the amount of funding available. In addition to highway type, it may be realistic to include at most two or three more parameters into the sampling scheme before the required sample size becomes too large to be economically feasible. In terms of the specific geometric and roadway characteristics to be included, horizontal curvature would certainly be the first choice. Vertical grade might be the second choice, and the presence/absence of paved shoulder and shoulder width the third choice.

The sampling scheme may take the following form if horizontal curvature and vertical grade are included with highway type:

- Highway Type.
  - Rural Interstates and Freeways
  - Rural Multilane Undivided Highways
  - Rural Two-Lane Highways
  - Urban Interstates and Freeways
  - Urban Multilane Undivided Highways
  - Urban Two-Lane Highways
- Horizontal Curvature.
  - Outside of Curve
    - $<= 3°$
    - $3° - 6°$

> = 6°

Inside of Curve

< = 3°

3° - 6°

> = 6°

Vertical Grade.

Upgrade

Downgrade

< = 2%

2% - 6%

> = 6%

The total number of combinations would be 6 highway types x 6 horizontal curvatures x 4 vertical grades = 144. Even if the sample size is reduced to only 50 expected encroachments per combination, the total required sample size would be 144 x 50 = 7,200 expected encroachments, or 16 times of that recommended for proposed study 1.

In summary, it is a very simple process to combine proposed studies 1 and 2 into a single study by modifying the sampling scheme of proposed study 1. The difficulty lies in the selection of specific geometric and roadway characteristics to be included into the sampling scheme and the resulting sample size requirement. While there is good argument for combining the two proposed studies 1 and 2, there are equally good arguments for conducting the two studies separately as originally proposed.

## ANTICIPATED RESULTS

The anticipated results from the study are:

1. Validation of encroachment frequencies/rates for use in the roadside safety cost-effectiveness model.

2. Encroachment frequencies/rates for various combinations of highway type and selected geometric and roadway characteristics for use in the roadside safety cost-effectiveness model.

3. Better understanding and data on the extent of unreported accidents.

## ESTIMATED COST AND TIME

Varies - function of the sampling scheme and required sample size.

# APPENDIX G. COMMENTS FROM EXPERT PANEL AND FHWA AND RESPONSES TO COMMENTS

## BACKGROUND

This appendix summarizes the comments received from the expert panel members during the meeting of April 29, 1992 and comments received from FHWA subsequent to the expert panel meeting and the responses to these comments. Note that the comments are grouped by expert panel member and not by subject matter. Also, there are duplications in some of the comments when similar comments were raised by more than one expert panel member or subsequently by FHWA.

## EXPERT PANEL COMMENTS

- Need sensitivity analysis on the encroachment model to identify important variables in order to limit data collection effort, i.e., research studies should concentrate only on those topics that have significant effects on the final outcomes of the model.

  Response. Extensive sensitivity evaluation has been conducted on the BCAP program under NCHRP study 22-8.[25] Results from the sensitivity studies were considered in developing the proposed data collection plans.

- Sample size too small for some of the studies.

  Response. The sample sizes proposed are the minimum sample sizes. Larger sample sizes are highly desirable, but need to be balanced against the associated costs. The project staff will review the sample size recommendations in finalizing the data collection plans.

- Need to better define the nature and purpose of the encroachment model.

  Response. More discussions on the nature and purpose of the encroachment model will be included in the final report.

- Proposed study 5 on relationships to injury severity most critical - make use of existing data whenever possible before embarking on expensive data collection effort.

  Response. The project staff agrees that the relationships to injury severity are the most critical components of the encroachment model and have the most effect on the outcome of the benefit/cost analysis. It should be borne in mind that the analysis involves comparison of alternative improvements. Encroachment frequency/rate and the resulting impact frequency/rate are common to all the alternatives and their effects are mostly canceled out when comparing among alternatives. On the other hand, severity is unique to each alternative and distinctly different among the alternatives. Thus, the effect of severity on the outcome of the benefit/cost analysis is more critical than that of the encroachment frequency/rate.

The project staff also agrees that existing data should be used to the extent possible. However, previous attempts to develop relationships to injury severity using existing data, such as police reported accident data, have met with only limited success. For example, average severity associated with various roadside objects and features has been developed based on police reported accident data. However, the data lack sufficient detail to address more specific questions such as the relationships of impact conditions to injury severity. It is still the belief of the project staff that indepth accident data, with sufficient detail to allow for reconstruction of the accidents to estimate impact conditions, are needed for the analysis.

- Combine proposed studies 1 and 2 by structuring the sampling scheme to include important variables, e.g., curvature, in the data collection effort to obtain observed impact frequencies.

<u>Response</u>. Proposed studies 1 and 2 can easily be combined into a single study by modifying the sampling scheme to include, in addition to highway type, any other variables, i.e., selected geometric and roadway characteristics, considered to have significant effects on the encroachment frequency/rate. This more direct approach of determining the encroachment frequency/rate associated with the various combinations of highway types and other selected geometric and roadway characteristics may seem appealing initially. It eliminates the intermediate step of using empirical adjustment factors and the concern over the use of single-vehicle, ran-off-the-road accident rates as the surrogate measure for encroachment rates in the determination of the empirical adjustment factors. However, there are also problems associated with this approach.

One problem with this approach is that the variables or geometric and roadway characteristics to be included in the sampling scheme will have to be pre-selected. This assumes sufficient prior knowledge to determine which variables are "more important" for inclusion in the sampling scheme. It may not be possible to assess the effects of other geometric and roadway characteristics not included in the sampling scheme, regardless of their significance on encroachment frequency/rate. In comparison, the approach in proposed study 2 allows the significance of the various variables on the encroachment frequency/rate to be determined on the basis of actual data and then develops the empirical adjustment factors accordingly.

Another and perhaps more important problem with this approach is the number of variables that can be included in the sampling scheme and the associated sample size requirements. The number of combinations and the associated sample size increase geometrically with the addition of each variable or levels within a variable to the sampling scheme. In proposed study 1, the sampling scheme includes 6 highway types with a sample size of 75 expected encroachments per highway type for a total of 450 encroachments. For illustration purposes, consider first the addition of horizontal curvature with six levels (e.g., outside versus inside of curves, and degree of curvature $<=3^\circ$, $3^\circ$ to $6^\circ$, and $>=6^\circ$) to the sampling scheme. The number of combinations in the sampling scheme is now increased sixfold to 36 (6 highway types x 6 horizontal curvatures). If vertical grade with four levels (e.g., upgrade, and downgrade with gradient $<=2\%$, $2\%$ - $6\%$, and $>=6\%$) are further added to the sampling scheme, the total number of combinations now becomes 144 (6 highway types x 6 horizontal curvatures x 4 vertical grades) or 24 times that of the original sampling scheme. With a sample size of 75 encroachments per combination, the required sample size would have increased geometrically from an initial total of 450 expected encroachments to 2,700 with horizontal curvature and 10,800 for both horizontal curvature and vertical grade. It is evident that the number of variables and the levels within each variable that can be added to the sampling scheme are very limited before the required sample size and the costs associated with the data collection effort would become economically prohibitive. It should also be borne in mind that the data collection effort is highly labor intensive, involving field monitoring of evidence of impacts on selected roadside objects.

The high costs associated with the field monitoring data collection effort is the main reason for designing two separate studies in the proposed data collection plan. Proposed study 1, with the labor intensive field monitoring effort, is limited to only averages or base encroachment rates for 6 highway types to keep the data collection effort to a minimum. The determination of the effects of the various influencing factors on encroachment frequency/rate are relegated to proposed study 2 which uses a totally different research methodology that does not require field monitoring of evidence of impacts. Instead, reported accident data from an existing data base are used in the analysis to develop empirical adjustment factors. This approach is relatively inexpensive and sample size is no longer an area of concern. Also, this approach does not require pre-selection of variables to be included in the sampling scheme, but allows the data to determine the relative importance of the various geometric and roadway characteristics on encroachment frequency/rate.

In summary, it is the opinion of the project staff that the advantages gained from combining proposed studies 1 and 2 into a single study is not worth the manyfold increase in the associated costs and is therefore not recommended.

- Unreported accidents constitute only a small percentage of accident cost and thus are of minor consequence. Use of reported accidents in prediction models would be better. Suggest parallel effort on accident based modeling studies.

Response. It is a reasonable assumption that unreported accidents are generally minor in nature, i.e., damage is not severe enough to disable the vehicles with minor or no injury to the occupants, and thus constitute only a small percentage of accident costs. On the other hand, unreported accidents could greatly distort the effectiveness of certain roadside safety devices if only accidents severe enough to be reported to law enforcement agencies are included in the evaluation.

It is arguable as to whether encroachment based models are better or worse than accident data based models for prediction of impact frequencies. Each approach has its advantages and shortcomings. More discussions on the pros and cons of both approaches are presented as follows. However, it should be noted that the proposed studies were developed with the specific objective of addressing the gaps in the state of the knowledge associated with the encroachment model. Thus, accident based modelling studies were not included in the list of proposed studies.

The primary advantage for an encroachment based model is its versatility. Since the encroachment model is not based on historical accident data, it can be used to predict the accident frequency of any roadside object or feature. It is applicable to newly constructed or reconstructed highways or for unusual situation not commonly found along highways. It can be used to assess multiple performance levels where there is no existing data since almost all of the current generation of roadside safety hardware were designed to a single performance level. Another major advantage of the encroachment based model is the greater level of detail the model can accommodate, such as different roadside conditions, varying traffic mixes, etc. Also, the model can predict the impact conditions which are important from the standpoint of estimating accident severity.

There are many limitations associated with the encroachment based model. First, the encroachment model is an indirect approach to predict accident frequencies, i.e., predictions of accidents are based on encroachments. As previously discussed under proposed study 1 (see appendix A), data on encroachments are very limited and subject to potential biases, such as controlled versus uncontrolled encroachments, presence of paved shoulders, and weather and surface conditions during data collection periods. There are numerous assumptions and algorithms built into the encroachment model, rendering it very difficult to validate the encroachment model.

Accident data based models are typically regression models developed from police reported accident data. Unlike the encroachment based model, this is a direct approach and the model is based on actual accident data. One limitation with an accident based model is that it is very specific in nature and thus not applicable to other roadside objects or features or to newly constructed or reconstructed highways or to situations with unusual roadway and/or roadside conditions. Another limitation is the extent of unreported accidents and the poor quality of police level accident data, such as inaccurate location coding, lack of detail, and miscoding of object struck, etc. There are also problems inherent with the regression technique. The number of variables that can be included in a regression model is relatively small. The regression models typically have very poor predictability and are dominated by the ADT term. The poor predictability of the regression models is really not surprising when one considers that accidents are rare and random events and the models typically do not include human factors which account for the majority of accident causative factors.

In summary, there are pros and cons with using either the encroachment based model or the accident data based model in the prediction of accident frequencies. However, given the current state of the knowledge, it is the opinion of the project staff that the encroachment probability approach is the only viable approach for a general purpose roadside safety cost-effectiveness procedure. This is the reason why most existing cost-effectiveness procedures are based on the encroachment probability approach and not on the accident data based modeling approach.

- Ambitious plan - cost and time estimates too low.

  Response. The project staff will review the cost and time estimates in finalizing the detailed data collection plans.

- Need to consider intended use of encroachment model. States do not have sufficient funding to do much improvement on the roadside. Suggested use of encroachment model for ranking/comparing alternate safety treatments. The final product must be simple to use to be accepted by States.

  Response. This point is well taken and recognized by the project staff.

- Question the use of encroachment model instead of accident prediction model. Models based on reported accidents should present lower bound values.

  Response. See previous response to similar comment.

- More statistics needed in the data collection plans, particularly with regard to required sample sizes.

Response. The emphasis of the detailed data collection plan was on the research approach and not on statistics. The statistical and analytical procedures recommended for use with the analyses are standard procedures and techniques that are well known to statisticians and readily available in statistical analysis packages, such as SAS. In terms of the sample sizes, the traditional or textbook approach of estimating sample sizes is not too meaningful given the many unknowns associated with the relationships. Instead, minimum required sample sizes are recommended in the data collection plans. Sample sizes larger than the minimum are always desirable, but need to be balanced against the associated costs. In the revised work plans, equations or formula for calculating the required sample sizes will be included for reference purposes.

- Need to have an overall schedule and time frame for the studies.

  Response. The overall schedule and time frame for the studies are at the discretion of FHWA. It is a function of which studies are selected and the level of funding available.

- Need to express the encroachment model in terms of equation(s).

  Response. An equation expressing the conditional probabilities will be added to the writeup in the final report.

- Suggest a single data collection effort for all proposed studies.

  Response. The proposed studies can be combined into one or two major data collection efforts if so desired by the FHWA. Again, it is a function of which studies are selected and the level of funding available.

- Cost per accident for indepth investigation too low. $1,000 per case would be more realistic. Also, data collection time period too short. Need to include chase time, quality control and data processing efforts in the estimates. Consider possibility of reducing the level of detail in the accident investigation to reduce data collection costs.

  Response. The project staff will reconsider the estimated cost per accident and the time requirements in revising the work plans for the final report. The level of detail envisioned for the indepth accident investigation is probably less than that of a typical National Accident Sampling System (NASS) case since occupant and injury data are not collected. The minimum level of detail required should be sufficient for reconstruction of the accidents to estimate impact conditions.

- Sample size too small to cover other influencing parameters, such as vehicle type, restraint usage, driver age, etc.

Response. The proposed sample sizes are the minimum required and are not sufficient to address too many other influencing parameters. The intent is to obtain some average values for use with the model. Again, there is a balance between the number of parameters that can be studied and the associated costs.

- Prefer accident based modelling to encroachment model.

  Response. See previous response to similar comment.

- Clear zone on 3R projects is major current concern.

  Response. None.

- If reported accident data are not suitable for validating encroachment rate, why are accident data proposed for use in developing adjustment factors?

  Response. Reported accident data are not suitable for validating encroachment frequency/rate in proposed study 1 because we are interested in the actual or absolute encroachment frequency/rate. Unless a good estimate on the extent of unreported accidents is available or if the extent of unreported accidents is very low, the use of reported accident data is not a good surrogate measure for encroachments.

  In proposed study 2 to develop adjustment factors for encroachment frequency/rate, we are not interested in the absolute encroachment frequency/rate, but only in the relative frequency/rate between locations with and without specific geometric and roadway characteristics. The basic premise is that the extent of unreported accidents would remain the same for both sites with and without specific geometric and roadway characteristics. Thus, the comparison of reported accidents for those sites would theoretically be the same as that for encroachments. Another assumption is that both encroachments and reported single-vehicle, ran-off-the-road accidents are affected by the same roadway characteristics. A third assumption is that roadside conditions are similar for all sites. Given these assumptions, it is possible to use reported single vehicle, ran-off-the-road accidents as the surrogate measure for encroachments in developing the adjustment factors.

- On field observation of impact frequency, why not include some key variables, e.g., curvature, in the sampling scheme to get better estimates directly rather than to use adjustment factors.

  Response. See previous response to comment on combining proposed studies 1 and 2 into a single study.

- Unreported accidents are only a small percentage of overall accident costs, why worry about them? Use reported accidents directly in the modeling effort.

  Response. See previous response to similar comment.

- Why use predicted impact frequency with the validation effort? This includes intermediate steps that can also be sources of error. The comparison between observed and predicted impact frequencies will reflect not only the encroachment rates, but also errors in the intermediate steps.

  Response. The project staff recognizes the potential problems associated with the use of predicted impact frequency in the validation effort. Indeed, the validation is not only on the encroachment frequency/rate, but also on the intermediate steps leading to the prediction of impact frequencies. However, given the study approach, it is necessary to include some of the intermediate steps except in special situations such as a longitudinal barrier located right on the edge of the travelway. Otherwise, intermediate steps such as the probability distribution function for the lateral extent of encroachment, encroachment angle and lateral offset (to determine the impact envelope) will have to be included in the prediction of impact frequencies.

- More thought needs to be given to defining homogeneous roadway segments. What are the key variables?

  Response. Much thought has been given to the definition of homogeneous roadway segments and the potential problems. Note that two of the three alternate categorization schemes, i.e., fixed length segments and unit segments, do not actually define homogeneous roadway segments. The key variables for defining homogeneity would be cross-sectional data elements (e.g., number of lanes, divided/undivided, presence/absence of shoulder, shoulder width, etc.), horizontal and vertical alignment, roadside conditions (e.g., sideslope, clear zone width, etc.)

- On injury severity, how to account for other influencing factors such as vehicle type, size, and weight, occupant age, restraint usage, secondary impacts, etc. The proposed sample sizes are too small to allow for evaluation of other influencing factors.

  Response. See previous response to similar comment.

- Consideration should be given to use of lower level of detail for indepth accident data to reduce data collection cost.

Response. The rationale for recommending indepth accident data in proposed studies 4 and 5 is that it is necessary to reconstruct the accidents to determine the impact conditions. Police or enhanced police level accident data simply do not have the required level of detail to allow for reconstruction of the accidents. Thus, as a minimum, the level of detail required for the indepth accident data should be sufficient for reconstruction of the accidents. The project staff is well aware of the high costs associated with collection of indepth accident data and is recommending only the minimum level of detail that is needed. For example, the investigation is limited to the inspection and documentation of the accident site and the involved vehicle. Driver and occupant information, including injury severity and details, are excluded from the investigation.

- Severity for impacts that exceeded the performance limit should not be an average value, but should still be a function of impact conditions.

Response. The severity for impacts exceeding the performance limit could still increase as a function of impact conditions in some instances. However, it would be very difficult to estimate the relationships between severity and impact conditions for those impacts exceeding the performance limit due to the variety of potential failure modes and the rare nature of such occurrences. Also, given that the severity of the impacts associated with exceeding the performance limits is already much higher than that for impacts in which the performance limits are not exceeded, average severity values should be adequate for the purpose of the encroachment model.

- Video monitoring in IVHS projects may be an inexpensive means of collecting encroachment data. Existing software to identify potential encroachments automatically. The encroachments can then be reviewed manually to determine controlled v. uncontrolled encroachments.

Response. Technological advances in video monitoring and electronic surveillance could some day provide a means to collect encroachment data at a reasonable cost. However, the project staff does not believe that we have yet reached that stage. IVHS projects are typically limited to urban Interstate highways where congestion and incident management are the key concerns. Thus, the existing setups may or may not be suitable for monitoring of encroachments. Also, the distinction between controlled and uncontrolled encroachments will remain a problem. There are other potential constraints when video monitoring is extended beyond urban Interstate type highways, such as source of power supply, availability of suitable vantage point for the video camera, limited coverage in terms of length of highway covered by the camera, lack of artificial lighting for nighttime monitoring, etc. Despite these potential problems and constraints, the feasibility of using video monitoring in IVHS projects to collect encroachment data should be further explored as a pilot study. Experience gained with the pilot study should be helpful in future endeavors to collect encroachment data on other highway types.

- Other existing literature to be considered - study by Galati on field observation of impacts with barriers, *TRB Special Report 214* in which Deacon attempted to validate encroachment rates with utility pole accidents.

  Response. The project staff are familiar with these literature and will consider them for potential use in revising the work plan.

- Functional class may not be a good surrogate measure. Breakdown by highway type, e.g., Interstate, multilane divided, multilane undivided, and two-lane undivided, may be a better alternative categorization scheme.

  Response. The use of functional class is a crude surrogate measure in an attempt to control for some of the major roadway and roadside characteristics. The suggested breakdown by highway type may be a better alternative and will be considered in the revision of the work plan.

**FHWA COMMENTS**

- Consider the pros and cons of combining proposed studies 1 and 2 into a single study.

  Response. See previous response to similar comment by expert panel.

- Consider the option of using reported accident data to validate encroachment frequency/rate, similar to the approach used in *TRB Special Report 214*.

  Response. In *TRB Special Report 214*, an attempt was made to validate encroachment frequency/rate using reported utility pole accident data. This approach is a viable approach if information is available on the extent of unreported accidents or if the extent of unreported accidents is expected to be relatively low, as in the case with utility pole accidents. However, such is not the case for many roadside objects or features. For example, the ratio of unreported to reported accidents for longitudinal barriers has been found to be as high as 47 to 1. The use of reported accidents as a means of validating encroachment frequency/rate would not be a good approach for these roadside objects with an unknown or large proportion of unreported accidents. Nonetheless, it is potentially a viable approach for use with some of the roadside objects.

- Consider the possibility of controlling for roadside conditions, such as sideslopes, clear zone width, and nature of hazard, in the study design.

Response. The control for roadside conditions is accomplished through the sampling scheme and in the selection of roadway segments for study. This is a critical consideration for proposed study 2 in which reported accident data are proposed for use in determining adjustment factors since the occurrence of single-vehicle, ran-off-the-road type accidents is largely a function of roadside conditions. One underlying or implicit assumption in the design of proposed study 2 is that the roadway segments have similar roadside conditions in order for the comparisons to be valid. The plan is to use roadway segments from the same or similar highways so that the roadside conditions would be essentially the same for the roadway segments without specifically controlling for roadside conditions.

- Consider the possibility of incorporating the approach used by Wright and Robertson into the study design.

  Response. The approach used by Wright and Robertson is certainly a viable alternative. The main reason for not proposing this approach is cost because of the labor intensive nature of the data collection effort. However, if a data base with detailed roadway and roadside data becomes available so that field data collection is no longer necessary, this approach would be very attractive and worth considering.

- Consider a pilot study on urban Interstate highways where breakaway luminaries and guardrails are readily available.

  Response. A pilot study to assess the viability of the study plan is a good idea and should be implemented prior to embarking on the full study. Urban Interstate highways would be a logical choice for the pilot study due to the ready availability of roadside objects suitable for monitoring. Also, the high traffic volume on urban interstate highways would mean higher frequency of encroachments, thus requiring shorter periods of monitoring.

- Consider the possibility of using the Michigan data base for the studies. The Michigan data base has information on guardrail inventory, including as a minimum, guardrail type, lateral offset, ADT and highway type. Also, starting this year, Michigan will have guardrail end as an entry in their accident reporting form and data base.

  Response. Given the availability of required data in the Michigan data base, it is logical to include Michigan as one of the study States. However, it would be desirable to include more than one State in the study so that the study results would have some geographical representation.

- Sideslope data in the existing data base for Alabama, Michigan, and Utah are very crude and non-uniform, e.g., sideslope data taken every 1/4 mi (402 m) within which the sideslope could have varied significantly. Advise against use of the existing data for proposed study 3 unless additional data are collected on roadside conditions.

Response. Given the limitations on the existing sideslope data, the reluctance to use the data for proposed study 3 is understandable. On the other hand, the costs associated with collecting additional data on roadside conditions would be substantial due to the labor-intensive nature of the data collection effort. The issue becomes whether the answer to the question of the severity of sideslopes is worth the additional cost involved. One suggestion is to use the existing data as a pilot study. If the results are promising, the study can then proceed with collection of additional data on roadside conditions.

- HVOSM simulation study in proposed study 3 would not be meaningful without taking vehicle orientation into account. Vehicle orientation should be included as part of impact conditions for proposed study 4.

  Response. The importance of vehicle orientation is well recognized. It is agreed that vehicle orientation should be included as part of impact conditions for proposed study 4. Vehicle orientation is intended as part of the data collection effort for proposed study 4 though not specifically delineated in the work plan. The work plan will be revised to place more emphasis on vehicle orientation data.

  In terms of the HVOSM simulation study, vehicle orientation, e.g., tracking and non-tracking, can be easily incorporated into the simulation matrix. The difficult part is to decide what are the typical vehicle orientations to use in the simulation effort. Results from proposed study 4 may provide the needed data to better define the simulation matrix in terms of vehicle orientation.

- With the current trend of airbag equipped vehicles, the severity of impacts with roadside objects and features will be significantly affected. Any study on severity should take restraint availability and usage into account. It may be advisable to postpone proposed study 5 until more airbag equipped vehicles are in the vehicle fleet.

  Response. The increasing availability of airbags as standard or optional equipment in the vehicle fleet and the gradual increase in the usage of seat belts could potentially have significant effects on injury severity. The argument that any study on severity should be postponed until the majority of the vehicle fleet is equipped with airbags is understandable. On the other hand, it can also be argued that we are in a constantly changing environment and that any study will have to be updated periodically to account for such changes. Also, the sampling plan can be tailored to oversample or even to include only airbag equipped vehicles. The drawbacks are potential for higher data collection costs due to the more restrictive sampling requirements and built-in biases, e.g., current airbag equipped vehicles are more likely to be the larger and more expensive makes and models.

## REFERENCES


1. *Guide Specifications for Bridge Railings, 1989*. American Association of State Highway and Transportation Officials, Washington, DC, 1989.

2. *Roadside Design Guide*. American Association of State Highway and Transportation Officials, Washington, DC, 1988.

3. *Guide for Selecting, Locating, and Designing Traffic Barriers*. American Association of State Highway and Transportation Officials, Washington, DC, 1977.

4. K. K. Mak, D. L. Sicking, and L. I. Griffin. *Development of Roadside Safety Data Collection Plan*. Interim Report, FHWA Contract No. DTFH61-90-C-00040, Federal Highway Administration, Washington, DC, September 1991 (unpublished).

5. K. K. Mak and D. L. Sicking. *Development of Roadside Safety Data Collection Plan*. Second Interim Report, FHWA Contract No. DTFH61-90-C-00040, Federal Highway Administration, Washington, DC, April 1992 (unpublished).

6. *Motor Vehicle Accident Costs*. Technical Advisory T 7570.1, Federal Highway Administration, Washington, DC, June 30, 1988.

7. *Accident Facts, 1991 Edition*. National Safety Council, Chicago, Illinois, 1992.

8. L. J. Blincoe and B. M. Faigin. *The Economic Cost of Motor Vehicle Crashes, 1990*. Publication No. DOT HS 807 876, National Highway Traffic Safety Administration, Washington, DC, September 1992.

9. J. W. Hutchinson and T. W. Kennedy. *Medians of Divided Highways - Frequency and Nature of Vehicle Encroachments*. Engineering Experiment Station Bulletin 487, University of Illinois, June 1966.

10. P. Cooper. *Analysis of Roadside Encroachments - Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces*. B. C. Research, Vancouver, Canada, March 1980.

11. L. R. Calcote et al. *Determination of the Operational Performance Requirements for a Roadside Accident Countermeasure Warranting System*. Final Report, FHWA Contract No. DOT-FH-11-8501, Federal Highway Administration, Washington, DC, 1984 (unpublished).

12. K. K. Mak and R. L. Mason. *Accident Analysis - Breakaway and Nonbreakaway Poles Including Sign and Light Standards Along Highways, Vol. II: Technical Report.* Publication No. DOT-HS-805-605, National Highway Traffic Safety Administration, Washington, DC, August 1980.

13. A. A. Lampela and A. H. Yang. *Analysis of Guardrail Accidents in Michigan.* Report No. TSD-243-74, Michigan Department of State Highways and Transportation, Lansing, Michigan, July 1974.

14. *Designing Safer Roads - Practices for Resurfacing, Restoration, and Rehabilitation.* Special Report 214, Transportation Research Board, Washington, DC, 1987.

15. C. V. Zegeer and M. J. Cynecki. "Determination of Cost-Effective Roadway Treatments for Utility Pole Accidents." *Transportation Research Record 970,* Transportation Research Board, Washington, DC, 1984.

16. W. F. McFarland, H. E. Ross, Jr., and T. C. Edwards. *Development of Design Criteria for Safer Luminaire Supports.* Appendix C, "Cost Effectiveness Study," NCHRP Report 77, Highway Research Board, Washington, DC, 1969.

17. P. H. Wright and L. S. Robertson. "Priorities for Roadside Hazard Modification: A Study of 300 Fatal Roadside Object Crashes." *Traffic Engineering,* Vol. 46, No. 8, Institute of Transportation Engineers, August 1976.

18. C. V. Zegeer et al. *Safety Effects of Cross-Section Design for Two-Lane Roads, Vol. I - Final Report.* Publication No. FHWA/RD-87/008, Federal Highway Administration, Washington, DC, October 1987.

19. L. I. Griffin and K. K. Mak. *The Benefits To Be Achieved From Widening Rural, Two-Lane, Farm-to-Market Roads in Texas.* Policy Development Report 0130-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, June 1987.

20. H. E. Ross, Jr., H. S. Perera, and K. K. Mak. *Clear Zone As A Function of Side Slopes for Rural Arterial Highways.* Draft Final Report, Study No. 2-8-90/1-990, Texas Transportation Institute, Texas A&M University, College Station, Texas, August 1990 (unpublished).

21. N. J. Deleys and L. O. Parada. *Rollover Potential of Vehicles on Embankments, Sideslopes, and Other Roadside Features. Volumes I and II, Final Report.* Publication No. FHWA/RD-86/146, Federal Highway Administration, Washington, DC, August 1986 (unpublished).



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