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16. Abstract

The report documents the development and application of methodology to inventory hazards and evaluate recommended safety improvements alongside controlled access highways and rural non-controlled access highways using one procedure and a common computer analysis program. Also included in the report is discussion of program output and interpretation of results.

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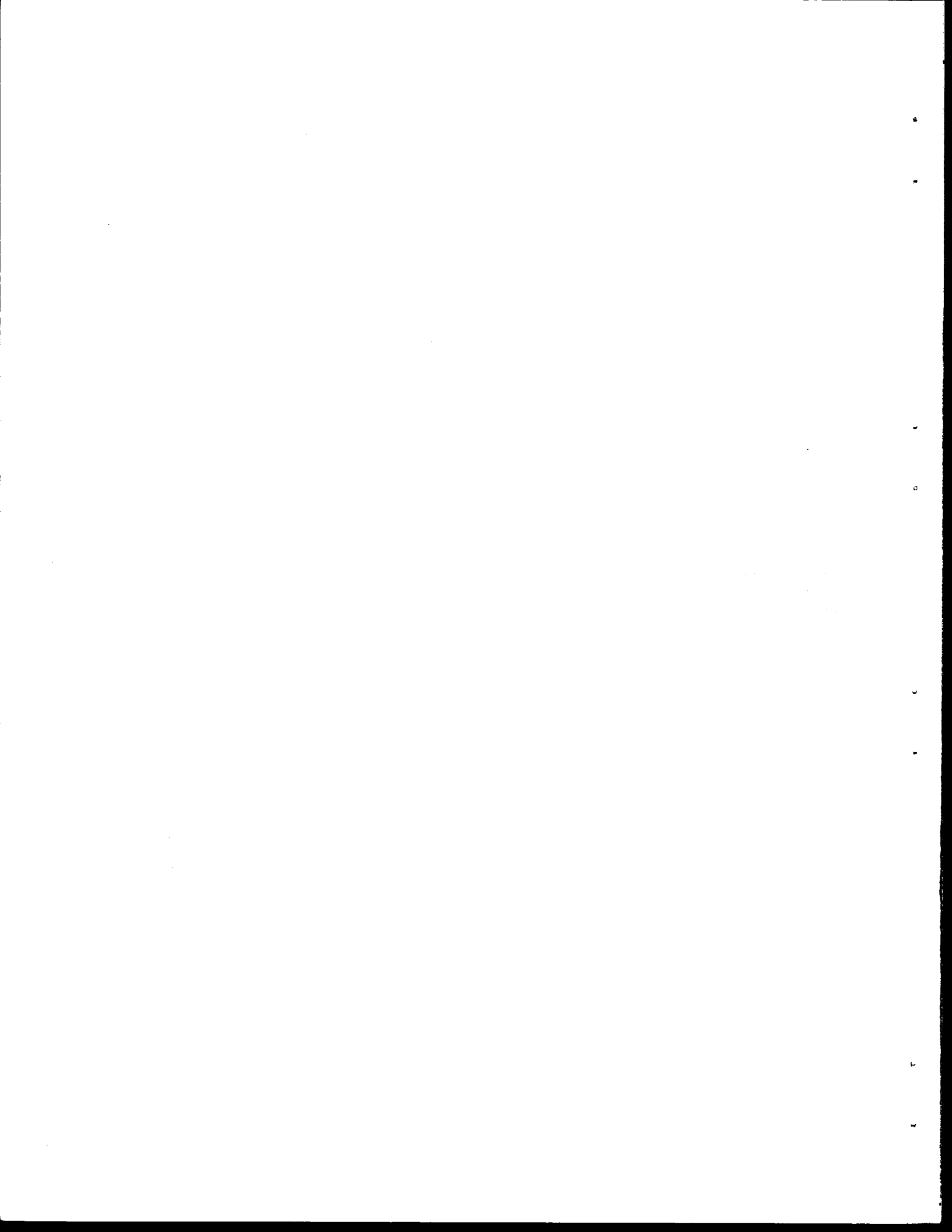
COST-EFFECTIVENESS EVALUATION OF ROADSIDE

SAFETY IMPROVEMENTS ON TEXAS HIGHWAYS

FINAL REPORT

by

Graeme D. Weaver

and

Donald L. Woods

Research Report 15-2F

Research Studies 2-8-72-11, 2-10-74-15, and 2-18-74-15

IMPLEMENTATION STATEMENT

The cost-effectiveness analysis procedure for roadside safety improvement evaluation has been developed on an immediate implementation basis. This report documents the rationale used in the development of the procedure, the field procedures to be applied in conducting the physical roadside hazard inventory and recommending safety improvements on Texas highways and the cost-effectiveness analysis computer program that currently is operational on SDHPT computer equipment. The material in this report currently is being implemented on a statewide basis.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

FOREWORD

This report, "Cost-Effectiveness Evaluation of Roadside Safety Improvements on Texas Highways," represents the final report of Research Study 2-18-74-15, entitled "Cost-Effectiveness Priority Program for Roadside Safety Improvements on Non-Controlled Access Roadways," a follow-on to Research Study 2-8-72-11, "Cost-Effectiveness Priority Program for Roadside Safety Improvements on Texas Freeways." The report documents the development and application of methodology to inventory hazards and evaluate recommended safety improvements alongside controlled access highways and rural non-controlled access highways using one procedure and a common computer analysis program. Also included in the report is discussion of program output and interpretation of results. A complete listing of the computer program is presented in the Appendix.
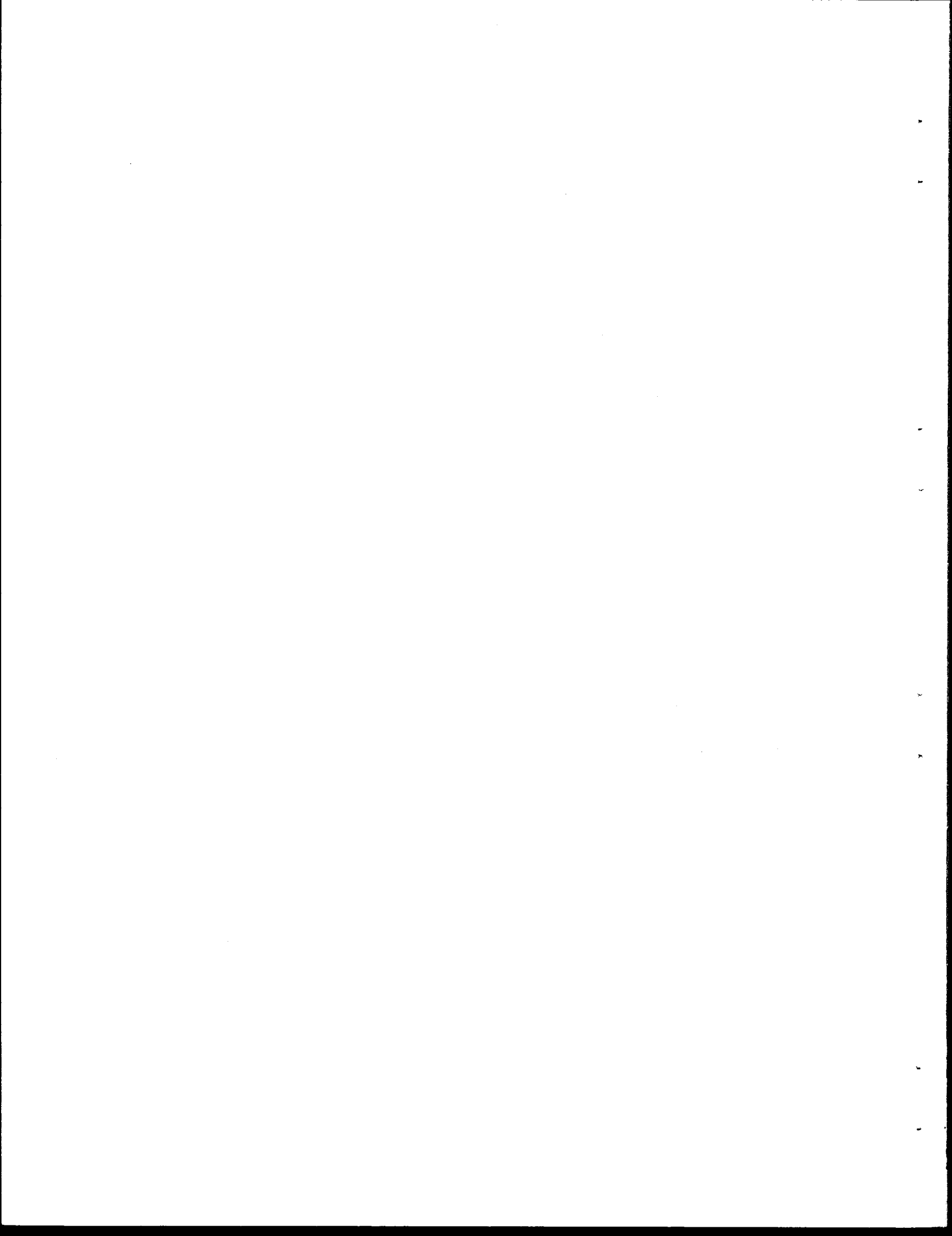
Special acknowledgment is given Messrs. Paul R. Tutt, Edwin M. Smith, and William R. Ratcliff of the Texas State Department of Highways and Public Transportation (SDHPT) and Mr. Ed Kristaponis (FHWA) for their cooperation and assistance through the developmental stages and field testing of the program. Their suggestions were invaluable in achieving an implementable research product. Appreciation is expressed to Mr. Jerry L. Dike (SDHPT Automation, Austin) for his assistance in adapting the cost-effectiveness analysis program to the SDHPT computer equipment.

iii

TABLE OF CONTENTS

TABLE OF CONTENTS, CONTINUED

1. INTRODUCTION

The Problem

On modern high-speed highways, a significant number of traffic accidents result from vehicles colliding with roadside obstacles. Such accidents comprise about one-half of the fatal accidents and 40 percent of all accidents on freeways ([1]). An examination of Texas fatal traffic accident statistics ([2,3]) revealed that from one-quarter to one-half of statewide fatalities involved single vehicles striking fixed objects or running off the roadway. Statistics such as these indicate the importance of roadside safety programs in the overall highway safety effort.

Roadside safety improvement programs, like any phase of highway construction or maintenance, must compete for limited funds. As increasing emphasis is being directed toward roadside safety and funds with which to achieve an acceptable safety level become more thinly spread, it is apparent that a definite need exists for methods to evaluate alternative safety improvements and to program such improvements for the greatest return within the budget constraints of available funds. This need was emphasized at the federal level by enactment of Standard 12 of the national standards for highway safety ([4]). To comply with this standard, each state must develop a formalized procedure to priority-rank safety improvements—the penalty for non-compliance being a potential 10 percent

1

cutback in construction funds.

Highways are constructed to standards that are current at the time, but safety technology is a dynamic process, continually changing. This evolution requires time during which highways must be built to satisfy immediate needs. Concurrently, safety technology expands as safety research provides more definitive criteria on which to further assess safety attributes. Each subsequent highway incorporates additional safety improvements over its predecessor as technology paves the way. Highways represent long-term entities--although the design life may be twenty years, most highways are expected to operate for several times the design life. The result is that many highways still in use today contain a myriad of roadside obstacles that stand as grim testimonials to potential death should a vehicle, for whatever reason, encroach on the roadside at high speed.

Obviously, economics prohibit the complete replacement of these highways with new facilities containing current safety features. They must be used to fulfill a vital need in the highway system. The only viable solution appears to be improvement through judicious expenditure of safety funds if these facilities are to be upgraded to safety standards compatible with the newer highways.

Objectives

The objective of this research was to develop a rational procedure for the programming of roadside safety improvements on controlled access highways and non-controlled access rural highways using cost-effectiveness analysis techniques. The research encompassed a three-year effort conducted in three consecutive studies. The objective during the first year was to develop procedures and methodology to accomodate only controlled access roadways (5,6,7). Efforts during the second year were directed toward field implementation of the procedures and modification where needed of the procedures and the analysis model to solve problems encountered, and to produce a more operational tool. Also during the second year, major emphasis was placed on adapting the controlled access procedures and model to the non-controlled access rural roadway environment (8,9,10). The third year's effort was directed toward implementation of the total procedure, modification where necessary, and assisting the sponsor in incorporating changes and attaining statewide implementation on an operational basis.

This report is written without regard to the individual annual work phases. Rather, it presents an overview of the total research product--one procedure and a single computerized analysis model capable of accommodating controlled access highways, both urban and rural, and rural non-controlled access highways.

3

The specific tasks within the study to achieve the objective are summarized below:

1. Identify those roadside obstacles that constitute a hazard;

2. Develop a procedure to systematically inventory roadside hazards existing along highways;

3. Develop a procedure to identify appropriate measures that may be taken to alleviate or reduce existing hazards;

4. Incorporate the above procedures into a computerized cost-effectiveness analysis model from which may be determined a priority ranking of improvement alternatives to assist administrators in developing safety improvement programs;

5. Validate the application procedure with field data.

The research was sponsored by the Texas State Department of Highways and Public Transportation (SDHPT); therefore, an important factor throughout the research was that the procedures developed be applicable on Texas highways and compatible with SDHPT policy and equipment. A further requisite was that the analysis of roadside safety improvement alternatives be based on a cost-effectiveness conceptual model developed in a National Cooperative Highway Research Program (NCHRP) research study (11). The NCHRP research produced a probabilistic conceptual model to be used as a management tool in establishing the priority for roadside safety improvements on freeways. The requirement that this research be applicable on a national scale resulted in a high degree of generalization in the

model and, therefore, it was not implementable in its current form

for specific needs. It was hoped that each state would adapt the

findings of the NCHRP research to its own specific needs and

administrative structure if the concept was to be implemented (12).

2. SAFETY IMPROVEMENT APPROACHES

Evaluation Methods

A highway safety administrator currently is faced with the problem of attaining goals that are becoming increasingly more difficult to achieve in light of escalating costs of material, labor, and an inflated economy in general. Within these constraints and the more stringent limitations on available safety funds, the choices of safety improvements that can be programmed are by necessity reduced to those which return the largest pay-off for the safety dollar. The realistic approach becomes one of evaluating, on a common basis, the safety improvement alternatives, ranking them on a priority scale, and including in a safety program those which yield the greatest economic return.

The principle of economic efficiency in expenditure to achieve the highest possible quality product is basic to good engineering practice. In relation to roadside safety, the product is hazard reduction. The two elements in the economic principle are divergent; thus, alternatives must be evaluated and trade-offs must be made to reach an acceptable level of stability. Further, if alternatives are to be evaluated uniformly across large regions, specific hazards and safety improvement alternatives must be identified, criteria must be selected to assure commonality in analysis, and procedures must be developed to apply the principle in the real world.

Safety improvement programs generally have consisted of a four-element procedure: (<u>11</u>)

1. Remove roadside obstacles.

2. Relocate those obstacles that cannot be removed. This includes moving to a protected location and moving laterally.

3. Reduce the impact severity of those obstacles that cannot be removed. This includes improvements such as breakaway devices, turning down guardrail ends, and flattening roadside slopes.

4. Protect the driver from those obstacles that cannot be improved otherwise, using impact attenuation or redirection devices.

This approach would be ideal if sufficient funds were available to accomplish all four steps. Under ever-present economic constraints, trade-offs must be made, even within each of the four basic steps. Which obstacles should be removed? Should certain obstacles be relocated, or can the same resulting safety benefit be achieved by design changes to reduce impact severity or to protect the driver using redirection devices?

The highway safety engineer is faced with the problem of evaluating many alternatives of this nature. Unfortunately, engineers have been handicapped by the lack of uniform objective criteria upon which to evaluate viable safety alternatives.

Several techniques have been used with varying degrees of success and acceptance, to systematically evaluate roadside situations. The strengths and weaknesses of the two most commonly used evaluation methods are discussed below.

Safety Evaluation by an Individual Engineer

Probably the most commonly used approach to recommending safety improvements has been the "engineering decision" approach in which an experienced individual is assigned the responsibility to evaluate the safety aspects of highways within a jurisdiction and recommend remedial action based on subjective criteria.

The effectiveness of this approach is influenced greatly by the technical capabilities of the individual, by his personal bias toward a particular safety improvement, and by the criteria upon which the evaluation of the hazard and its subsequent improvement are made. Many times, the decision to install a safety device or incorporate a major design change is based on publicity given some recent spectacular accident. Decisions made under emotional public pressure that generally is exerted in cases like this, could be made more rationally if evaluation criteria were developed.

Uniformity of recommended improvement is difficult, if not impossible, to attain between adjacent sections of roadway under the jurisdiction of separate individuals. This does not present major problems if the total roadway mileage under consideration is

small enough to be accommodated effectively by one authority. In this situation, the criteria employed become, in effect, uniform. However, the region under consideration generally is sufficiently large that several individuals are required, each evaluating hazards under his own personally selected criteria.

Personal bias toward particular safety improvements is difficult to remove and can heavily influence the recommended action. For example, an individual in one region believing that the installation of guardrail represents the best way to reduce the hazard associated with a rigid sign support is less apt to recommend other viable alternatives. His counterpart in the adjacent region, perhaps having been exposed to several spectacularly lethal collisions with guardrail, possibly would advocate any safety alternative except guardrail. The result would be indiscriminant usage in the one region and a conspicuous lack of guardrail in the other.

The individual approach can be used effectively under certain circumstances; however, the key to its success lies in the establishment of uniform criteria under which the evaluation and analysis are made.

Evaluation by a Safety Team

The use of a safety team has gained acceptance particularly in spot improvement programs. As a minimum, the team generally includes personnel trained in traffic operations, roadway geometrics, and safety. Depending on the degree of sophistication of the

safety program and the availability of personnel in specialized areas of expertise, the team also may contain human factors specialists, law enforcement personnel, maintenance engineers having cost-estimating experience and others including selected citizens who are not otherwise connected with the agency.

The safety team offers partial solution to some of the undesirable attributes of the individual engineer approach. It is reasonable to expect that the assemblage of a safety team is the result of a decision to systematically organize a unified approach toward safety improvement evaluation. Further, the team concept reduces the possibility of personal bias toward a particular hazard treatment due to the varied points of view by which each hazard is evaluated. Also, it is reasonable to assume that guidelines and evaluation criteria will be established which will provide the necessary continuity and uniformity throughout the total jurisdiction.

Evaluation Criteria

Throughout the discussion heretofore, the need for objective evaluation criteria has been stressed. To evaluate safety improvement on economic principles necessarily involves a relation between costs and a quantified improvement. The quantification of "improvement" may be in terms of reduced impact severity or in terms of some other benefit derived from the expenditure of funds.

Cost-effectiveness analysis relates the improvement cost to the degree of hazard reduction achieved in comparison to the existing situation. Glennon (11) defined cost-effectiveness as the ratio of the annualized cost of improvement to the hazard reduction achieved, or the cost to eliminate one fatal or serious injury accident. A primary advantage of cost-effectiveness analysis is that it does not involve the highly emotional and arbitrary value of human life that must be used in other analyses. The effectiveness measure is one of hazard severity reduction in accordance with predetermined goals rather than direct societal costs. If hazard severity can be quantified for particular roadside obstacles, the hazard reduction between two alternatives can be used as a relative measure of effectiveness. Thus, alternatives may be evaluated on the basis of cost required to achieve the hazard reduction goal.

Cost-effectiveness analysis, thus, is particularly applicable in scheduling roadside improvements to obtain the greatest return for the safety dollar invested.

3. A COST-EFFECTIVENESS MODEL

Every segment along a roadway has an associated degree of road-side hazard for vehicles traveling through that segment. The hazard may be relatively small for a flat slope free of fixed objects while on the other hand, the hazard may be very high for a steep side slope or a large rigid object near the edge of the roadway (11). The degree of potential hazard is influenced by proximity to the roadway and by the severity of resulting impact if the object is struck. The severity can be assumed to be independent of distance, that is, the severity associated with striking a rigid object located ten feet from the roadway is no different than if the same object was struck at fifty feet from the roadway. The probability of encroaching the latter distance, however, is much smaller. Also influencing the potential hazard is the probability that a vehicle will encroach on the roadside at a location such that the obstacle is in the vehicle path and will be impacted. This is a function of the traffic volume and expected encroachment rate, the latter being derived empirically from research. Obviously, a small discrete obstacle exhibits a smaller probability of being struck than does a continuous obstacle such as a guardrail at the same offset distance. To strike the discrete obstacle, a vehicle must leave the roadway within a relatively small segment whereas it may collide with the guardrail after leaving the roadway anywhere along the rail length. The severity of striking the rigid obstacle may

be extremely high as is the case for a bridge pier. On the other hand, the severity of striking the guardrail is substantially less. Therefore, trade-offs must be considered--probability of impact versus severity of impact--in many situations.

If quantitative measures can be assigned to these influencing parameters and costs associated with improvement alternatives can similarly be determined, cost-effectiveness techniques may be used to evaluate various recommended safety improvements. To accomplish this, the following data are required:

1. Each hazard must be identified and assigned a relative degree of hazard (severity index);

2. Encroachment distances and frequency must be defined;

3. Feasible alternatives must be defined for each hazard or group of hazards;

4. Annual maintenance costs and repair costs per collision for both the existing situation and the improved situation must be determined;

5. Cost-effectiveness analysis procedures must be developed utilizing the quantified parameters;

6. To obtain uniformity, a codified procedure must be developed whereby specific data may be collected in a consistent manner to provide necessary input for analysis on uniform criteria.

A conceptual cost-effectiveness model was developed by Glennon (11) to evaluate safety improvements on freeways. The theoretical model forms the basic analysis technique for evaluating safety improvements in the implementation procedure developed in this research. The conceptual model is dependent upon many informational needs including hazard dimensions, location with respect to the roadway, and severity associated with impact. In addition, expected vehicle operating characteristics such as roadside encroachment frequency and distance must be defined. Some of these data may be obtained only from on-site inspection, others may be described mathematically from research findings in related areas. The cost-effectiveness analysis model will, to a large degree, dictate the hazard information that must be determined in the field. This element of the conceptual design is discussed first because it forms the nucleus of the proposed implementation procedure.

In developing his conceptual hazard model for freeways, Glennon (11) concluded that a sequence of three conditional events must occur to result in a vehicle-obstacle collision:

1. The vehicle must be within the increment of roadway associated with the roadside obstacle;

2. The vehicle must encroach upon the roadside;

3. The vehicle must travel a sufficient lateral distance to impact the roadside obstacle.

14

On these conditions, Glennon formulated a conceptual approach for evaluating the degree of hazard considering vehicle exposure; vehicle encroachment rate; and severity, size and lateral placement of the roadside obstacle. He then proposed the general equation:

$$H = V \, [P(E)][P(C/E)][P(I/C)] \; . \; . \; . \; . \; \text{(Eqn. 1)}$$

where

> H = The Hazard Index; expected number of fatal plus non-fatal injury accidents per year.

> V = Vehicle exposure; number of vehicles per year passing through increment, L.

> $P(E)$ = Probability that a vehicle will encroach on the roadside within increment L; encroachments per vehicle. This probability is a function of the length of exposure, L, and other environmental variables such as the geometric design of the roadway.

> $P(C/E)$ = Probability of a collision given an encroachment has occurred; accidents per encroachment. This probability is a function of the angle of encroachment, θ; the vehicle's lateral displacement (measured from the right-front corner of the vehicle), y; the lateral placement of the roadside obstacle, s; and the size of the obstacle, ℓ and w.

> $P(I/C)$ = Probability of an injury (fatal or non-fatal) accident given a collision; fatal plus non-fatal injury accidents per total accidents.

For a given angle of encroachment, Glennon's model becomes (11):

$$H = \frac{E_f S}{5,280} \left[\ell \int_s^\infty f(y)\,dy + \int_\ell^{\ell+d\csc\theta} \int_{s+(x-\ell)\cos\theta\sin\theta}^\infty f(y)\,dy\,dx \right.$$

$$\left. + \int_{\ell+d\csc\theta}^{\ell+d\csc\theta+w\cot\theta} \int_{s+d\cos\theta+(X-\ell-d\sec\theta)\tan\theta}^\infty f(y)\,dy\,dx \right] \quad \ldots \quad \text{(Eqn. 2)}$$

The above are identified in Figure 1.

Glennon simplified his equation by replacing the double integrals by approximately equivalent single summations. Thus, using a vehicle width of 6 ft., an 11-degree encroachment angle, and a 50-50 directional split (half exposure per roadway), his hazard model becomes (5):

$$H = \frac{E_f S}{10,560} \left[\ell P[y \geq s] + 31.4\ P[y \geq s+3] \right.$$

$$\left. + \frac{5.14w}{n} \sum_{j=1}^{n} P[y \geq s+6+\frac{w(2j-1)}{2n}] \right] \quad \ldots \quad \text{(Eqn. 3)}$$

16
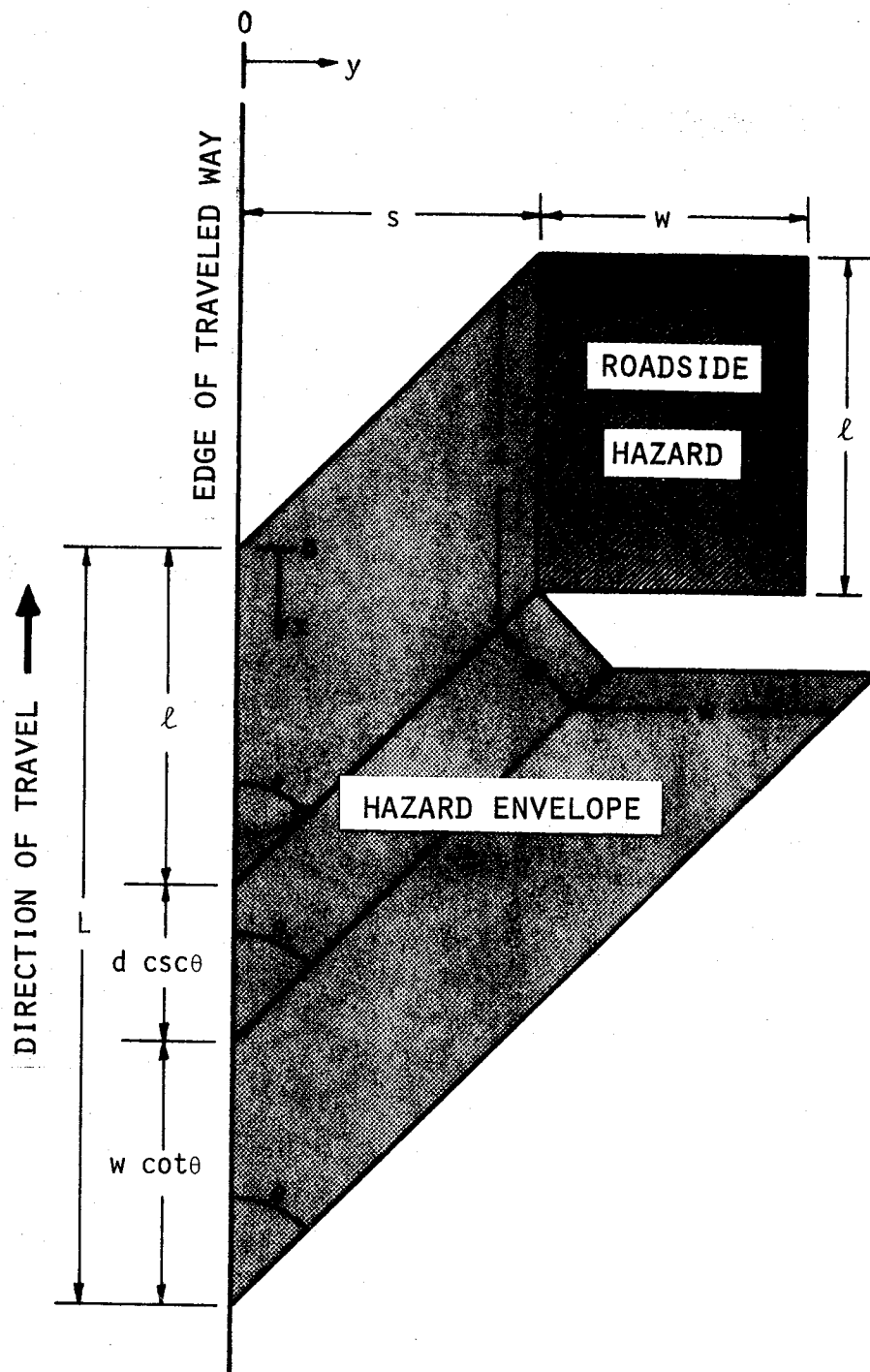
Figure 1. Schematic illustration of roadside obstacle and
its relationship to an encroaching vehicle. (11)

where

H = Hazard Index, number of injury (fatal or non-fatal) accidents per year, associated with a one-directional roadway. For median analysis, the Hazard Index is computed for each roadway separately, and the two measures are added.

E_f = Encroachment frequency, number of roadside encroachments per mile per year.

S = Severity Index, the number of fatal and non-fatal injury accidents per total accidents.

ℓ = Longitudinal length of the roadside obstacle, feet.

w = Lateral width of the roadside obstacle, feet.

y = Lateral displacement, in feet, of the encroaching vehicle; measured from the roadside edge of the traveled lanes to the outside front corner of the vehicle.

s = Lateral placement, in feet, of the roadside obstacle; measured from the roadside edge of the travel lanes to the longitudinal face of the roadside obstacle.

$P[y \geq ...]$ = Probability of a vehicle lateral displacement greater than some value.

n = Number of analysis increments for the hazard associated with the obstacle width. A reasonable subdivision is; for widths up to 4 feet, one increment for each 2.5 feet of width.

j = The number of the obstacle-width increments under consideration starting consecutively with 1 at the increment furthest downstream. The encroachment length, $w\cot\theta$, is divided into a number, n, of small increments, j=1, n, and the contribution of each increment to the Hazard Index is calculated using the lateral displacement for the mid-point of the subsection.

4. RESEARCH APPROACH

Conceptual Design

Glennon's conceptual analysis model for freeways provides a basic foundation for a structured method by which safety alternatives may be evaluated; however, it is not readily implementable in its current state. Its operation is dependent on many obstacle and traffic informational needs that are unique to a particular roadway. If the conceptual model is to be developed into an operational tool, methodology must be designed to acquire and synthesize the informational needs, and present them in a manner that is amenable to the analysis requirements of the conceptual model. Further, the concept must be extended to evaluate safety improvements not only along freeways, but on non-controlled access roadways as well.

The objective of the research reported herein was to develop methodology to implement a roadside hazard improvement evaluation program using, as an analysis tool, Glennon's basic cost-effectiveness model. The adaptation of the resulting procedure to computerized analysis techniques was a primary requisite in the conceptual design of the research.

The procedural concept summarized below was developed to achieve the research objective:

1. Identify the conceptual model informational needs (input data necessary for analysis). Determine which data may be obtained from previous research studies and which data would necessitate additional research.

2. Examine the currently available information to determine (a) which portion is usable immediately in its current format, and (b) which portion would require modification or restructuring for input use.

3. Develop methods to obtain the informational needs that are not currently available.

4. Develop computerized techniques to incorporate the model required data and permit evaluation of recommended safety improvements.

5. Test the procedure under actual highway implementation conditions.

The summary is expanded in the following paragraphs.

Analysis Model Requirements

Glennon's conceptual model requires specific hazard information (dimensions, location, etc.), traffic operating characteristics (speed, expected encroachment frequency, encroachment distance, etc.), quantification of impact severity, and cost information associated with existing and improved condition. It was planned that those informational needs that were available from previous research results would be used in this research effort. For example, vehicle

20

encroachment characteristics have been studied extensively by several researchers (13,14,15). Results of these studies were evaluated to determine if they were suitable in their published state for model input or if further research in this area was necessary.

Those requirements for which information was not currently available were identified and means to obtain them were investigated. These included such factors as hazard severity quantification (severity index) and cost information for existing roadside obstacles and improved configurations.

Obtaining Informational Needs

A fundamental task in the conceptual design involved definition of a roadside "hazard." From this, it was necessary to identify those roadside obstacles to which the definition applied. Since specific hazard information was to be used as computer input, a prescribed format was necessary to describe each applicable roadside obstacle. Similarly it was necessary to identify improvement alternatives for each hazard and devise a procedure to record this information in a prescribed format. Also, cost information must be obtained for input to the analysis model.

Hazard severity information was not readily available for many roadside obstacles. Results from previous research studies involving full-scale vehicle crash tests provided quantified definition of impact of such roadside appurtenances as sign posts, luminaires, roadside slopes, and guardrail, bridge rail, or other

21

vehicle deflection devices. Information was not available, however, to describe relative severity of impact with trees, culverts, inlets, and other obstacles found alongside the roadway.

Evaluation Procedure

The intent of the computerized evaluation analysis was that it perform not only the cost-effectiveness mathematical computations, but that it be structured so that all possible alternatives could be evaluated with a minimum of input information. Therefore, it was desirable to incorporate, within the analysis model, hazard severity information, vehicle encroachment information and other such information that was independent of a particular obstacle. This would reduce the input requirements to specific hazard information such as dimensions and location, and specification of a particular improvement.

Testing the Procedure

A stage-testing program was conceived to assure compatibility between the concept and real-world application. It was planned that as each task within the research study was completed, it would be tested under conditions expected in final implementation. Use of a corresponding development/test procedure would identify deficiencies in each phase prior to initiation of the next.

Research Tasks

The research tasks outlined to apply the theoretical concept on existing highways were as listed below:

1. Identify those obstacles that constitute a hazard to a vehicle encroaching on the roadside;

2. Assign a quantified severity index to each applicable roadside obstacle;

3. Define vehicle encroachment criteria under which roadside obstacle can be expected to be impacted;

4. Develop a procedure to locate obstacles existing alongside roadways and a mechanism to record the information needed for analysis of the existing hazard;

5. Define viable safety alternatives for each applicable hazard;

6. Develop a mechanism to select safety alternatives for each hazard or group of hazards identified, and record the information for comparative evaluation of the selected alternatives;

7. Develop computer techniques to incorporate the information collected in steps 1 through 6, and analyze the alternatives on a cost-effectiveness basis;

8. Test the hazard identification list, the inventory procedure, the alternative selection procedure, and the computer analysis model.

5. DEVELOPMENT OF APPLICATION PROCEDURE

The development of the procedure and discussion of the application of the mechanism to implement the research approach are presented in this section.

Identification of Roadside Hazards

The decision to computerize the safety evaluation procedure dictated that all roadside hazards be specifically identified. Basic to identifying roadside hazards is the definition of those roadside obstacles that are considered to be hazardous. Hazard connotes severity of impact. Technically, any roadside obstacle projecting above the ground surface, any surface depression, or any terrain feature which produces a vector change in vehicle acceleration can be considered a hazard.

To define those obstacles that should be included in the hazard inventory, a list was compiled to include known roadside obstacles meeting the above general definition of a hazard. In compiling the basic list, no regard was given to the severity of impact. The basic list contained approximately ten categories into which obstacles could be classified.

Field trials on existing highways were conducted to determine deficiencies in the basic list. These trial inventories revealed not only additional obstacles that had been omitted from the basic list, but the need for further sub-classification within the basic

categories to fully define obstacles found alongside the roadway.
Several extensions and refinements were made as a result of con-
tinued field trials.

A primary requisite for inclusion of a roadside obstacle in
the hazard list was that it was one to which some safety improvement
could be recommended. Since the objective of the research was to
evaluate safety improvements, it was considered impractical to in-
clude, in the hazard identification, those obstacles serving pri-
marily the function of preventing vehicle-to-vehicle conflicts
(operational conflicts) or other obstacles as discussed below.

Each roadside obstacle has associated with it some degree of
hazard. However, certain obstacles such as sign posts and luminaire
supports, through the advanced technology in breakaway concepts,
have been designed such that the hazard of impact is virtually
negligible. Also, the state of technology is such that very little
can be done to reduce the impact severity below its current level.
Therefore, breakaway sign supports and luminaire supports were ex-
cluded from the hazard identification list.

Other roadside obstacles are placed along highways for opera-
tional control and, although their presence constitutes a hazard,
if omitted, would allow operational maneuvers that would produce
greater hazard. Post and cable installations placed between main
lanes and frontage roads or in the median to prohibit intentional

vehicle crossover are an example. Similarly, median barriers and fences fall within the same category. These obstacles may be inventoried as a matter of record, but no improvements are offered.

Channelizing islands at grade-intersections on non-controlled access highways were excluded from the inventory. These operational control elements were considered necessary for orderly traffic flow and, as such, would not be removed. Right-of-way fences similarly were removed from the basic identification list.

Other roadside obstacles that were not inventoried included buildings or other fixed objects adjacent to non-controlled access highways passing through urban areas, or control devices not within the jurisdication of a highway department such as railway grade crossing warning devices.

The resulting list of roadside obstacles selected on the above rational is presented in Table 1. Uniformity of hazard identification is essential to the operation of a computerized analysis technique. Therefore, each roadside obstacle has been assigned an input code as shown in Table 1.

Hazards were grouped by descriptive title under general identification code designation and, where necessary, each general classification was sub-divided into several categories with each being identified by a descriptor code designation. This classification system allowed greater flexibility in recording hazards by permitting the addition of new general categories or, more often, additional descriptor codes when "special" or unusual hazards were encountered.

TABLE 1

HAZARD CLASSIFICATION CODES

Note: Circled Codes denote Point Hazard

Identification Code	Descriptor Codes
(01.) Utility Poles	(00)
(02.) Trees	(00)
(03.) Rigid Signpost	(01) single-pole-mounted (02) double-pole-mounted (03) triple-pole-mounted (04) cantilever support (05) overhead sign bridge
(04.) Rigid Base Luminaire Support	(00)
05. Curbs	(01) mountable design (02) non-mountable design less than 10 inches high (03) barrier design greater than 10 inches high
06. Guardrail or Median Barrier	(01) w-section with standard post spacing (6 ft-3 in.) (including departing guardrail at bridge) (02) w-section with other than standard post spacing (including departing guardrail at bridge) (03) approach guardrail to bridge--decreased post spacing (3 ft-1 in.) adjacent to bridge (04) approach guardrail to bridge--post spacing not decreased adjacent to bridge (05) post and cable (06) Metal Beam Guard Fence (Barrier) (in median) (07) median barrier (CMB design or equivalent
07. Roadside Slope	(01) sod positive slope (02) sod negative slope (03) concrete-faced positive slope (04) concrete-faced negative slope (05) rubble rip-rap positive slope (06) rubble rip-rap negative slope

08. Ditch   (00)
(includes erosion,
rip-rap runoff ditches,
etc.--does <u>not</u> include
ditches formed by inter-
section of front and
back slopes

(09) Culverts

    (01) headwall (or exposed end of pipe
          culvert)
    (02) gap between culverts on parallel
          roadways
    (03) sloped culvert with grate
    (04) sloped culvert without grate

(10) Inlets

    (01) raised drop inlet (tabletop)
    (02) depressed drop inlet
    (03) sloped inlet

(11) Roadway under Bridge
     Structure

    (01) bridge piers
    (02) bridge abutment, vertical face
    (03) bridge abutment, sloped face

12. Roadway over Bridge
     Structure

    (01) open gap between parallel bridges

    (02) closed gap between parallel
          bridges
    (03) rigid bridgerail--smooth and con-
          tinuous construction
    (04) semi-rigid bridgerail--smooth and
          continuous construction
    (05) other bridgerail--probable penetra-
          tion, snagging, pocketing or
          vaulting
    (06) elevated gore abutment

13. Retaining Wall

    (01) face

    (02) exposed end

(14) Miscellaneous Point
     Hazards

    (01) pedestal base > 6 in. above
          ground, < 1 ft. diam.
    (02) pedestal base > 6 in. above
          ground, > 1 ft. diam.
    (03) historical monument < 1 ft.
          wide
    (04) historical monument > 1
          ft. wide

Any code additions would necessitate computer program modification prior to implementation. Table 1 includes a comprehensive list of hazards, but it is anticipated that additional descriptor codes will be needed to accommodate all hazards that can be found along the roadway. Provisions were made in the computer cost-effectiveness analysis program to include these as the need arises.

Severity Index Assignment

The Severity Index is the relative measure of an obstacle's ability to produce a given outcome on the vehicle and/or occupants when a collision occurs. To quantify the severity of the applicable roadside hazards, a two-part questionnaire was developed to distribute throughout the State of Texas to individuals in professions related to highway safety. These professions included the areas of design, operations, maintenance, law enforcement, and administration.

The first part of the questionnaire consisted of ninety-eight hazard comparison statements to which an "agree" or "disagree" response was requested. The second part consisted of an evaluation of fifty-two roadside hazards and conditions; the respondent was requested to numerically rate the potential hazard of each on a one-to-ten linear rating scale. A rating of zero indicated negligible injury to vehicle occupants, and a 10-rating indicated an assumed fatality.

The linear scale while convenient for consistent ratings from field personnel, has some inherent disadvantages in the cost-

ASSUMPTIONS

SEVERITY INDEX	% PDO ACC.	% INJURY ACC.	% FATAL ACC.	ACC. COST
4	40	59	1	8180
5	30	65	5	16,710
6	20	68	12	30,940
7	10	60	30	66,070
8	0	40	60	124,000
9	0	21	79	160,100
10	0	5	95	190,500

BASED ON

$ 200,000	per	Fatality
10,000	per	Injury Accident
200	per	PDO Accident
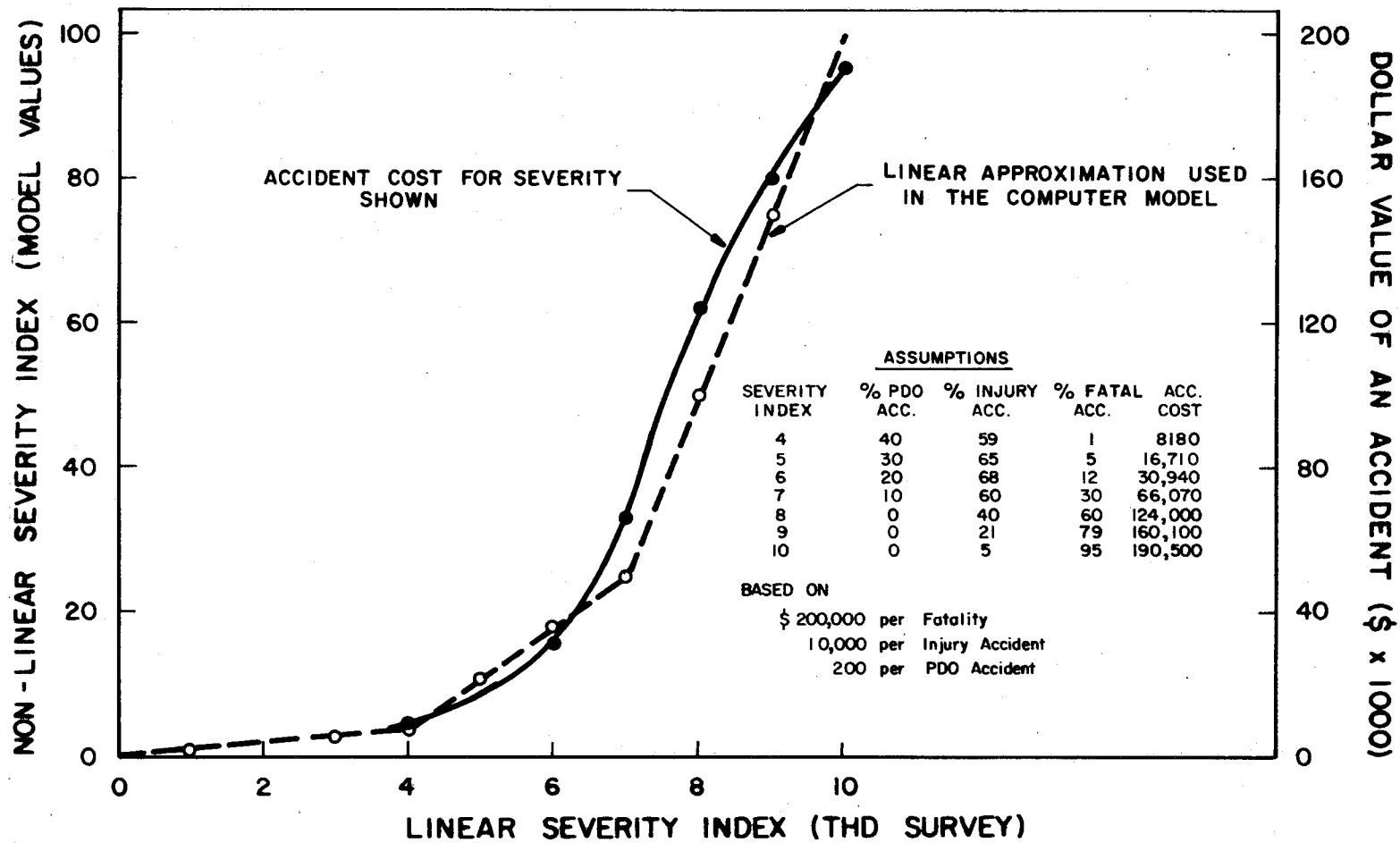
Figure 2. Severity index adjustment relationships.

effectiveness model. In particular, a unit numerical change in the Severity Index means two entirely different things depending upon the end of the scale involved. For example, a change from 9 to 7 represents a reduction from a highly probable fatal impact to one producing only injury, whereas a similar numerical change from 4 to 2 represents only minor significance, both being in the property damage only region of severity. Therefore, the linear severity indices were adjusted on a non-linear scale essentially the same as the cost relationships associated with Property Damage Accidents only (PDO), Injury Accidents (I), and Fatal Accidents (F).

To establish a relationship between linear and adjusted severity indices and associated costs, it was necessary to make some assumptions regarding the percentage of PDO, Injury, and Fatal accidents that could be reasonably expected to occur from collision with obstacles that had been previously assigned a severity index on a linear scale. The resulting adjustment process was developed subjectively by a committee of research staff and safety engineers directly related to the study. To establish minimum and maximum limits, it was assumed that a linear index of zero would represent a collision producing only property damage. At the other extreme, a severity index of 10 represented collisions producing almost certain fatality. Therefore a 95 percent fatality and 5 percent injury rating was assigned to the linear index of 10. Further, from experience with accidents, it was assumed that the distribution of PDO, injury and Fatal Accident between these two extremes would best be represented by a classical S-shaped curve similar to that shown in

Figure 2. The percentages of PDO, injury and fatal were then estimated using the basic curve form as a guide.

The cost data used to adjust the Severity Index represent rounded values from a U. S. Department of Transportation preliminary report (16). The PDO cost values presented in the report were applicable to both urban and rural accidents. Therefore, to more appropriately reflect only the higher speed rural accidents, and assuming a factor due to increased repair costs, the PDO costs used in the severity index adjustment were $700 per accident rather than $515 stated in the Department of Transportation document. The costs used were: $200,000 per fatality accident, $10,000 per injury accident, and $700 per property damage only accident.

The total accident costs associated with the assumed distribution were then computed using the U.S. DOT costs as shown in Table 2 and non-linear severity indices were established by the resulting curve form presented in Figure 2. The non-linear severity indices (ordinate, Figure 2) represent the linear indices (abscissa, Figure 2) using the total accident cost distribution (solid curve, Figure 2) as a transformation. The maximum accident cost ($200,000) representing a severity index of 100 on the non-linear scale represents a severity index of 10 on the linear scale. It became apparent that the assumptions regarding the cost per accident did not appreciably influence the relationship provided the total cost for a fatal incident was equated to 10 on the linear severity index scale.

For computer programming, the curve presented in Figure 2 was

32

TABLE 2

ASSUMPTIONS
IN THE DEVELOPMENT OF THE NON-LINEAR
SEVERITY INDICES

Linear Severity Index	% PDO Accidents	% Injury Accidents	% Fatal Accidents	Total Accident Cost
0	100	0	0	$ 700
1	85	15	0	2,095
2	70	30	0	3,490
3	55	45	0	4,885
4	40	59	1	8,180
5	30	65	5	16,710
6	20	68	12	30,940
7	10	60	30	66,070
8	0	40	60	124,000
9	0	21	79	160,100
10	0	5	95	190,500

TABLE 3

COMPARISON OF LINEAR AND NON-LINEAR HAZARD INDICES

Linear Severity Index	Severity Index Based on Cost	Approximation Using Three Linear Equations	Percentage Difference
0	0	0	NA
1	1	1	0
2	2	2	0
3	3	3	0
4	4.5	4	+12.5
5	8.6	11	+27.9
6	15.5	18	+16.1
7	33.0	25	−32.0
8	62.0	50	−19.3
9	81.0	75	− 7.4
10	95.5	100	+ 4.8

approximated by a series of three linear relationships:

$$Y = X \text{ for the region } 0 < X \leq 4$$

$$Y = 7X - 24 \text{ for the region } 4 < X \leq 7$$

$$Y = 25X - 150 \text{ for the region } 7 < X \leq 10$$

Using these equations results in some substantial differences within the linear severity range of 4 to 7 as indicated in Table 3. The approximation was closer for the upper limits. These differences were, however, considered to be acceptable particularly in light of the subjective manner used to establish the linear severity indices and to convert to the non-linear indices.

Definition of Vehicle Encroachment Characteristics

The quantification of certain traffic operating characteristics is vital to successful usage of Glennon's conceptual cost-effectiveness model. Specifically, the information required includes: (1) roadside encroachment frequency, (2) encroachment orientation, (3) lateral displacement, and (4) vehicle speed. The definition of these operating characteristics for inclusion in the analysis model is based on previous research in the particular areas.

Vehicle encroachment data have been compiled by several researchers (13,14,15) with similar findings. The extensive work in this area by Hutchinson and Kennedy (13) provided the basic data for the conceptual model. Distributions of encroachment frequency and lateral displacement developed by Hutchinson and Kennedy and included in the analysis model are shown in Figures 3 and 4.
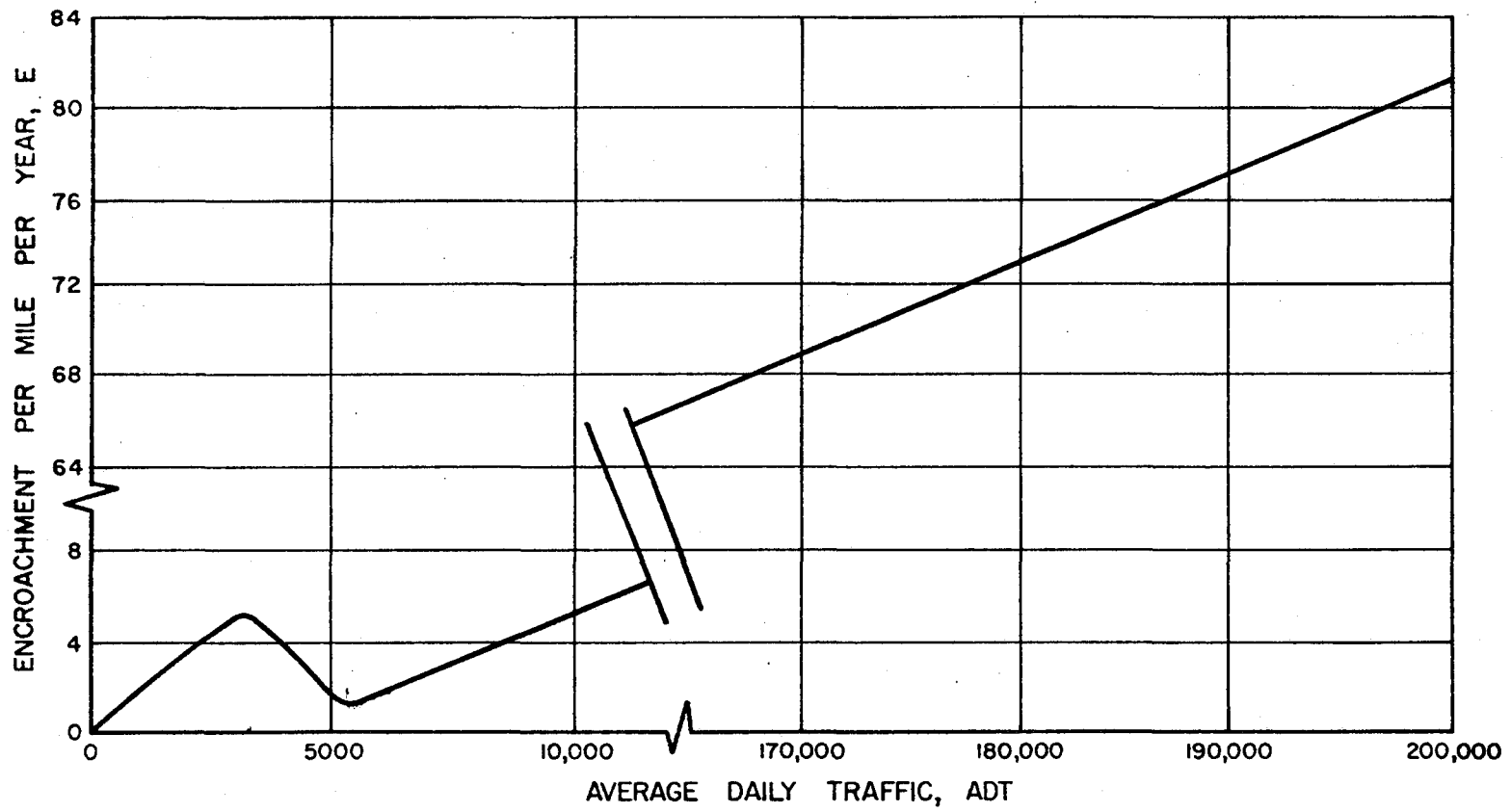
Figure 3. Roadside encroachment frequency. (11)
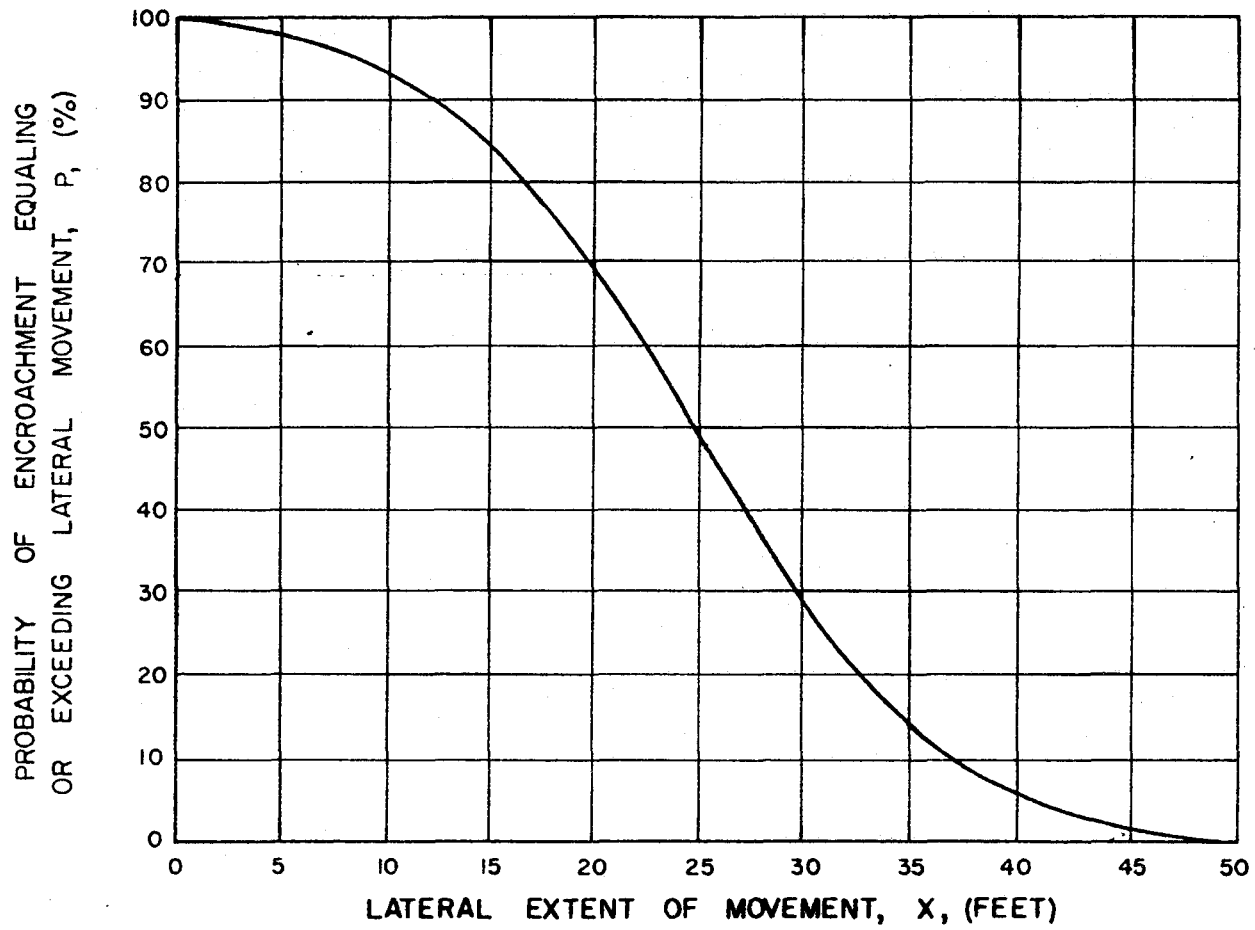
Figure 4. Distribution of lateral displacements of encroaching vehicles. (11)

Since Glennon's model is dependent upon a single encroachment angle, it was necessary to select a particular angle for the analysis procedure. The range of expected encroachment angles has been documented in previous research. Hutchinson and Kennedy (13) reported that approximately 85 percent of the vehicles departing the roadway did so at an angle of 25 degrees or less. Garrett and Tharp (14) determined the mean departure angle at the shoulder to be 3.7 degrees for speeds in the 60 to 70 mph range. Weaver and Marquis (17) in conducting full-scale vehicle tests on roadside slopes reported that the 25-degree encroachment angle commonly used in barrier structural tests (18) appeared higher than could reasonably be expected to occur at high operating speeds. Glennon (11) in an attempt to select a single encroachment angle for general usage, developed lateral displacement distributions for encroachment angles of 3, 11, and 25 degrees. He selected the 11-degree angle because it closely approximated Hutchinson and Kennedy's (13) overall distribution. Since studies of accident data in Texas (19) revealed that the mean angle of median barrier impacts was 11 degrees, the 11-degree encroachment angle selected by Glennon was used in this research, and is shown in Figure 4.

A 60-mph vehicle speed was selected for analysis purposes.

Obtainment of Hazard Informational Needs

The hazard associated with a roadside obstacle is influenced by its dimensions and its location with respect to the travel lanes. These parameters are significant factors in determination of the hazard index in the cost-effectiveness analysis.

Two approaches were considered during the developmental stages

to obtain location information for each identified hazard in the field. It was first thought that hazard dimensions, longitudinal position (milepoint) and lateral offset could be determined from the road-inventory log sheets or from "as-constructed" plans maintained by the Texas SDHPT. Initial attempts to obtain the necessary data from these sources revealed that in many cases, the recorded information differed appreciably from the actual field situation. In most comparisons, the information on structures was accurate; however, information for hazards such as trees, signs, guardrail and slopes was not sufficiently accurate to use in the analysis model. It was found that many obstacles recorded in the plans did not now exist, and others, such as guardrail installed as a field change, were not shown on the plans. Therefore, locating existing roadside hazards from these sources was infeasible.

The second approach considered involved the conduct of a detailed physical inventory of the highway under consideration. This method, although more time-consuming than the first approach, would permit accurate determination of all necessary roadside obstacle information. The inventory technique offered several other advantages also. Its use made possible an on-site perspective assessment of the hazard with respect to the roadway cross-section and the relationship of one hazard to others in the immediate vicinity. In many cases, an on-site inspection would be necessary to fully evaluate potential remedial treatment. The need for precise hazard location, in conjunction with the requisite for on-site remedial evaluation, led to the decision to conduct a physical inventory of the total roadway. From this decision evolved the basic concept of hazard inventory and improve-

ment recommendations being conducted simultaneously by a safety team in the field.

Having selected the field inventory technique as the most feasible method to locate existing roadside obstacles, consideration was given to developing a methodology to conduct the inventory. To accomplish this, it was necessary to develop solutions to the following questions:

1. Who would conduct the inventory?

2. What measurement technique could be used to locate existing obstacles within the desired accuracy yet allow the inventory to progress as rapidly as possible?

3. What mechanism was necessary to record the hazard information?

4. How could improvement alternative recommendations be made?

5. What mechanism was necessary to record the improvement alternatives to be evaluated?

In examining the above questions, it became apparent that utilization of a safety team would best satisfy the requirements of questions 1 and 4. Use of a team rather than one individual would alleviate the undesirable attributes of the single-evaluation concept discussed earlier. Also, a team could not only locate and identify existing hazards, but if the team composition was selected under specific experience criteria, the existing hazard could be assessed in the field and viable alternatives recommended at the site. The evaluation process could be accomplished concurrently with existing hazard information collection; thereby obtaining both existing and improvement information

during only one inventory.

Since many miles of highway would be inventoried, conducting the inventory with a vehicle was considered necessary rather than requiring the evaluation team to walk. Longitudinal location of existing hazards estimated to the nearest five feet was considered acceptable. Since vehicle odometers may be purchased commercially with recording capabilities of one-thousandth of a mile, use of this technique was selected to locate existing hazards with respect to known milepoints along the roadway. Locating obstacles in this manner eliminated the need for standard field survey techniques and greatly reduced the time required for the inventory process. The procedures to locate obstacles are discussed in more detail later in this report.

Recording Existing Hazard Information

Uniformity in inventory procedure and content is essential to the operation of a computerized analysis technique. The extremely large number of hazards that must be inventoried along the highway required the use of a systematic coding process to record the existing hazard information for eventual analysis by the computer model. Several ways were investigated to accomplish this. The feasibility of manually entering the data directly on computer cards in the field was evaluated. This approach was rejected due to the limited writing space available on cards and difficulties that could be expected in key-punching from this source.

The use of portable electronic equipment (similar to a typewriter) which could be used to record data and subsequently transfer the information to computer cards or magnetic tape was rejected due

41

to the high costs involved. Use of this equipment would necessitate specialized training for inventory personnel.

The approach taken involved manual recording on a one-page form designed to contain all necessary information to describe each roadside obstacle included in the hazard inventory list. The hazard inventory form, shown in Figure 5, was developed in several stages and represents the culmination of repeated field trials and modifications resulting therefrom. The form is applicable for controlled access roadways and non-controlled access rural roadways; the analysis procedures being accommodated internally within the computer analysis model depending on the highway type and classification code entered on the form.

Definition of Safety Improvement Alternatives

To define possible safety improvements for each applicable hazard, an approach similar to that used in establishing the hazard list was taken. Using brainstorming techniques, an extensive list was developed to include possible improvements for each obstacle in the hazard inventory list. This list was further expanded to include improvements to groups of obstacles that would be expected to occur along the roadside. During the development of this phase, any suggested improvement was included in the list without regard to cost, resulting severity, or to a certain degree to the practicality of the improvement. The basic list was taken to the field repeatedly to determine deficiencies, and extended or refined as

ROADSIDE HAZARD INVENTORY

Inventory Conducted by_____ Date_____ Hazard Description_____

HIGHWAY

1 2	3 4 5 6	7	8 9 10	11 12 13 14	15 16	17 18	19 20 21	22
Highway Type	Highway Number	Classification	County Code	Control Number	Section Number	Total Width: Center-Line to Shoulder on Inventory Side (Undivided Highway Only)	ADT (Total Both Directions 1000's)	Recording Direction

Highway Type
00 US Spur
01 US
02 SH
03 SH Spur or Loop
05 FM-RM
06 US Alternate
08 IH

Classification
Full Control Access
1. Interstate
2. Non-Interstate
Non-Control Access
3. Two-Lane
4. Multilane Divided
5. Multilane Undivided
Other
6. One-Way Frontage Rd.
7. Two-Way Frontage Rd.

Recording Direction
1. With Milepost
2. Against Milepost

BOX 1

HAZARD CLASSIFICATION

23 24 25 26	27 28	29 30	31	32 33 34	35 36 37 38
Hazard Number	Identification Code	Descriptor Code	Offset Code 1. Right 2. Median or Left Side	Median Width (ft) (Leave Blank if Median Inventoried on Near Side Only)	Grouping Number

MILE POINT AT HAZARD

39 40 41 42 43 44	45 46 47 48 49 50
Beginning	End (Except for Point Hazard)

BOX 2

POINT HAZARDS

/ 51	52 53		54 55 56	57 58 59	60 61 62	63 64 65
	Hazard Offset, D (ft)		Width (W) (ft)	Length (L) (ft)	Height (ft) or	Depth (ft)

Drop Inlets Only

BOX 3

LONGITUDINAL HAZARDS (Curbs, Bridgerails, Barriers, Guardrails, Ditches, and Retaining Walls)

2 51	52 53	54 55	56 57 58	59 60	61	62
	Beginning	End	Height (ft) or Depth (ft)	Width (W) (ft)		

Hazard Offset, D (ft)

END TREATMENT — Guardrail Only

61
1. Not Beginning at Structure - Safety Treated
2. Not Beginning at Structure - Not Safety Treated
3. Beginning at Structure - Full-Beam Connection
4. Beginning at Structure - Not Full-Beam Connection

62
1. Not Ending at Structure - Safety Treated
2. Not Ending at Structure - Not Safety Treated
3. Ending at Structure - Full-Beam Connection
4. Ending at Structure - Not Full-Beam Connection

BOX 4

SLOPES
FRONT SLOPE

3 51	52 53	54 55	56 57	58 59	60 61	62 63	64	65
	Beginning	End	Beginning	End	Beginning	End	Slope Face Erosion Code 1. Slight or None 2. Severe (Ruts >1 ft.)	Slope Direction 1. Positive 2. Negative

Hinge Point Offset, D_0 (ft) — Steepness :1 :1 — Distance "D_1" (ft)

2nd or BACK SLOPE (Except for Level Terrain)

66 67	68 69	70 71	72 73	74	75
Beginning	End	Beginning	End	Slope Face Erosion Code 1. Slight or None 2. Severe (Ruts >1 ft.)	Slope Direction 1. Positive 2. Negative

Steepness :1 :1 — Distance "D_2" (ft)

BOX 5

| / | Card Type
77

Recommendations:_____
_____
_____
_____

Figure 5. Roadside hazard inventory form.

43

necessary until a final list was selected.

Recording Safety Improvement Information

After identifying the applicable safety improvement alternatives for each hazard or group of hazards that would be inventoried, a mechanism was needed to record the selected improvement information. Since the improvement information formed the "after" condition which is compared to the existing hazard in the analysis, it was considered desirable to develop a data-input system compatible with the hazard inventory input.

A roadside hazard improvement form was designed to provide a system whereby feasible safety improvements for each category of hazards could be coded. This form provided a mechanism to record improvement information in a prescribed format that would be acceptable for computer analysis. The improvement form shown in Figure 6 was developed as a result of repeated field trials, as was the hazard inventory form.

Hazard Inventory Form

The information recorded on the hazard inventory form provides the necessary data to completely describe the existing hazard from which the base hazard index is computed for improvement alternative comparison in the cost-effectiveness analysis model.

Each inventory form constitutes a single computer card data input source and a separate form is used to inventory each roadside

ROADSIDE HAZARD IMPROVEMENTS

BOX 1

1 2 3 4	5 6 7 8	9 10 11	12 13 14 15 — 16 17	Hazard and Improvement Description
Hazard Number	Highway Number	County Code	Control Number / Section Number	

18 19 20 21 22 23	Repair Cost per Collision ($) 24 25 26 27 / 28 29 30 31	Normal Maintenance ($/yr) 32 33 34 35 / 36 37 38 39
First Cost of Improvements ($)	Hazard / Improvement	Hazard / Improvement

POINT HAZARD IMPROVEMENTS

BOX 2

/1/ (40 41) Alleviate Hazard — 42:
1. Remove
2. Make Breakaway and/or Relocate
3. Reconstruct Inlet to Safe Design
4. Reconstruct Cross-Drainage System (Remove Headwalls, Extend Culvert, Grade, Etc.)

/1/ /2/ (40 41) Protect Hazard with Guardrail (Hazard Not on Critical Slope) — Lateral Offset (ft) Right or Median Near Side 42 43 — Lateral Offset (ft) Median Far Side 44 45

/1/ /3/ (40 41) Protect Hazard with Concrete Median Barrier (CMB) — Lateral Offset (ft) 42 43

/1/ /4/ (40 41) Protect Hazard with Energy Attenuation System — Length (ft) 42 43 44 — Width (ft) 45 46 — Offset (ft) 47 48

LONGITUDINAL HAZARD IMPROVEMENTS

BOX 3

/2/ /1/ (40 41) Curb — 42:
1. Remove and Regrade
2. Install Wedge Modification

/2/ /2/ (40 41) Bridgerail — 42:
1. Rigid
2. Semi-rigid
— 43:
1. Upgrade to Full Safety Standards
2. Move Laterally (Complete Box A)
3. Install Guardrail Along Bridgerail Face
4. Deck Over Gap Between Parallel Bridges and Install Single Bridgerail (Complete Box A)

/2/ /3/ (40 41) Guardrail — 42:
1. Remove Existing Guardrail
2. Upgrade to Full Safety Standards (Complete Box B if applicable)
3. Upgrade to Full Safety Standards and Close-up Gap (Complete Box B)
4. Close-up Gap Between Existing Guardrail (Complete Box B)
5. Anchor Existing Guardrail to Bridgerail
6. Safety Treat Guardrail Free-End Only

/2/ /4/ (40 41) Ditch — 42:
1. Reshape to Safe Cross Section
2. Replace with Storm Drain
3. Protect with Guardrail (Complete Box A)
— 43

SLOPE IMPROVEMENTS

BOX 4

/3/ /1/ (40 41) Install Guardrail to Protect Slope Not at Bridge — May Include Point Hazards on Slope (Complete Box A) — 42 43

/3/ /2/ (40 41) Install Approach or Departing Guardrail at Bridge — May Include Point Hazards on Slope (Complete Box A) — 42 43

/3/ /3/ (40 41) Install Continuous Guardrail Between Successive Bridges

/3/ /4/ (40 41) **FLATTEN SLOPE**

FRONT SLOPE — Hinge Point Offset (D_0)(ft) Beginning 42 43 / End 44 45 — Steepness :1 Beginning 46 47 / End 48 49 — Distance "D_1" (ft) Beginning 50 51 / End 52 53 — Slope Direction 54: 1. Positive 2. Negative

2nd or BACK SLOPE — Steepness :1 Beginning 55 56 / End 57 58 — Distance "D_2" (ft) Beginning 59 60 / End 61 62 — Slope Direction 63: 1. Positive 2. Negative

Beginning 64 65 66 67 68 69 — End 70 71 72 73 74 75 — Milepoint of Improved Slope (Complete If Different From Inventory)

BOXES A & B

Box A (Install Guardrail)

Right or Median Near Side or Approach Guardrail — Lateral Offset (ft) Beginning 44 45 / End 46 47 — Median Far Side or Departing Guardrail — Lateral Offset (ft) Beginning 48 49 / End 50 51

Box B (Changes to Existing Guardrail)

Lengthen (ft) Beginning 43 44 45 46 / End 47 48 49 50 — Shorten (ft) Beginning 51 52 53 54 / End 55 56 57 58

BOX 5

/4/ (40) No Improvement Recommended

/2/ (77) Card Type

Figure 6. Roadside hazard improvements form.

obstacle. The form was developed to permit direct transfer of inventory data to computer card for entry to the cost-effectiveness program. Only those data within the numbered spaces in each box will be entered on computer cards, the number below each space denoting the column number on the computer card.

The inventory form was designed to record data in five categories. For purposes of discussion, these categories are labeled Boxes 1 through 5 on the form to identify a particular block of data contained within each data category. Box 1 contains highway and geographical information. Box 2 contains hazard classification information and specific hazard location information. The information in these two boxes is essential to the computer program operation. Space is also provided at the top of the form to identify the hazard by general name in words for manual review of the forms.

Hazards were classified into three categories: (1) point hazards, (2) longitudinal hazards, and (3) slopes. Since any roadside obstacle encountered can be classified in only one of these categories, only the information within the box containing the particular hazard type must be recorded on the form to fully describe the hazard.

Boxes 1 and 2 must be completed on every form. In addition to Boxes 1 and 2, only one of Boxes 3, 4, or 5 will be completed on each form.

The format was simplified as much as possible to assist the key-punch operator in transferring the data to cards. Data spaces

46

were located in a straight line reading from left to right and all
spaces between consecutively key-punched columns were closed up.
A circle appears in the left margin adjacent to each row of data
spaces. Since only certain rows of spaces must be key-punched
from each form, and these rows may differ between consecutive
forms, a check mark (√) placed in the circle adjacent to the appro-
priate completed row of spaces will allow the key-punch operator
to quickly locate the data to be key-punched from that form. The
circles adjacent to Boxes 1 and 2, "Card Type" (column 77) contain
pre-printed check marks because the data in these rows of spaces
must be key-punched from every form.

It is emphasized that a check mark should be placed in a
circle along the left margin adjacent to any row or data spaces
in which entries are made. If the check mark is omitted, the key-
punch operator may overlook certain data.

Each required data entry on the inventory form must be
recorded in a prescribed manner. Proper completion of the form is
discussed in the subsequent section of this report.

Hazard Improvement Form

The information recorded on the hazard improvement form de-
scribes the recommended safety treatments and provides the data
for computation of the "after" condition hazard index for cost-
effectiveness analysis.

The format of the form is similar to that of the hazard inventory form, and the general discussion of the left-margin circles for check marks, hazard dimensions and hazard classification within the three categories also applies to completion of the improvement form. The improvement form, applicable for all types of rural highways, has undergone extensive field trial on rural and urban Interstate highways and limited field trial on rural non-controlled access highways. The improvement form was designed to record five categories of data, identified for discussion purposes as Boxes 1 through 5. Two centralized locations on the form, identified as Boxes A and B pertain to guardrail information which may be common to other categories on the form. Whereas the information on the inventory form pertained to the hazard as it existed at the time of inventory, all information (dimensions, offsets, etc.) on the improvement form pertain to the improved situation recommended. Each improvement form constitutes a single computer card data input source. Only the data within the numbered spaces in each box will be entered on computer cards.

Box 1 and the card type (column 77) contain preprinted check marks in the left margin circles. The information in the rows of data adjacent to the check marks must be completed on every form. In addition to Box 1 and card type, only one of Boxes 2, 3, 4, or 5 will be completed on each form. Box A or B will be completed only when directed by certain improvement alternatives listed in Boxes 3 or 4.

The form was designed to permit selection of only those improvement alternatives that are compatible with a particular hazard type. Therefore, point hazard improvements may be recommended only for point hazards, longitudinal hazard improvements only for longitudinal hazards, and slope hazard improvements only for slope hazards. The "No Improvement Recommended" alternative may be specified for any of the three primary classifications of hazard.

Development of Computer Analysis Model

The cost-effectiveness analysis is reduced to a repetitive computational procedure after improvement costs are defined and hazard severity indices are quantified. The computational procedures to determine the hazard indices, although cumbersome by manual techniques, are easily accommodated by computer after quantifying the necessary input data.

A computerized procedure assures uniformity in analysis of improvement alternatives for a particular hazard type. This removes intentional or unintentional bias toward a particular improvement, and provides a consistent base for selection of one improvement alternative relative to another.

These factors were instrumental in the decision to computerize the safety improvement procedure. Also, the hazard inventory information recorded during the safety improvement program, would serve other uses to complement existing data bases. At the completion of the roadside hazard inventory, an extensive file of all

existing roadside obstacles would be available. Using currently
available computerized file-generation programs, selected portions
of this information may be accessed quickly to develop cost esti-
mates of proposed work, establish maintenance programs, and for
other routine budgeting and operational tasks.

The primary objective in developing the analysis model was to
provide an analysis technique in which the input requirements were
minimized and the alternative/consequence evaluations maximized
within the model. The use of the model and discussion of the
resulting output are discussed in the next section of this report.
The appendix contains a computer listing of the analysis model.

General Procedure

The application procedure to evaluate safety improvements for
roadside hazards comprises three related functions as summarized:

1. Conducting a detailed physical inventory of the high-
   way system to identify and locate each roadside hazard,

2. Recommending feasible safety improvement alternatives
   for each hazard or for groups of hazards, and

3. Evaluating the recommended safety improvement alterna-
   tives using a computerized cost-effectiveness analysis
   model.

In the inventory phase, each applicable hazard is located
longitudinally along the highway by milepoint using a vehicle equipped
with an odometer capable of recording to one-thousandth of a mile

(approximately 5 ft.). As each hazard or group of hazards is located and evaluated, recommendations for remedial action necessary for safety improvement are made. Hazard inventory information and improvement recommendations are recorded on the forms designed for this purpose and described earlier in this report. These two data sources—existing hazard inventory information and improvement recommendations—provide the basic input information for analysis by the cost-effectiveness model.

The following section presents detailed discussion of the application of the procedure including instructions for completion of the forms, computer operation requirements, and interpretation of the analysis results.

6. APPLICATION

A primary consideration throughout this research was that the procedures developed be implementable on existing highways. Therefore, considerable attention was devoted to assuring that the procedures and mechanisms developed could be applied within real-world constraints, primarily time constraints. Conducting an inventory procedure, such as is required in this endeavor, constitutes a substantial expenditure in terms of personnel and equipment. To minimize these costs, methods and measuring devices were designed to obtain the hazard informational needs as easily and quickly as possible yet with the necessary accuracy.

This section of the report describes the application procedure. Included are discussions of the lateral boundaries of the inventory, suggested team composition, and detailed usage of the inventory and improvement forms. Also, the computer input requirements are described. A discussion of resulting data output and how it may be used to develop a safety improvement program concludes the section. Five hypothetical sets of inventory and improvement data input are presented in Appendix B to illustrate the procedure for using the two forms that are discussed in this section.

Scope

The lateral boundaries within which safety improvements will be made are administrative decisions, although accepted practice in

most existing roadside improvement programs has been to consider the primary and secondary recovery areas (30-ft. lateral clearance) as generally sufficient. From available information (11) safety improvements within this region would benefit approximately 85 percent of drivers encroaching the roadside. The inventory procedure developed in this research includes all applicable roadside hazards located in the median or within a 30-ft. lateral distance adjacent to the outer edge of the traveled lane. In particular cases involving steep slopes, the 30-ft. lateral distance must be exceeded. This is discussed later in this report.

The Inventory Team

It is apparent that the quality of the analysis depends to a very large degree on the quality of the input data. Since the recommendations for alternative safety improvements will govern to a great extent the cost-effectiveness results, the inventory team must include personnel having considerable experience in traffic operations, geometric design, maintenance, and cost-estimating. Field trials of the inventory procedure indicated that a four-person team represents an efficient working force, to include as a minimum a driver, a data recorder, and two decision-makers to recommend safety improvements. The more experienced the team members, the more flexibility is afforded to rotate duties. The following was one procedure that was found to work very efficiently. The driver assumed the responsibility of identifying each hazard as

he drove along the highway at low speed, and stopped adjacent to the hazard to read the odometer. All hazard inventory data were recorded by one member of the team who was familiar with the hazard inventory form. The driver called out hazard milepoint and identified the hazard by name. These were recorded and necessary identification codes assigned. Offset distances and other applicable data were recorded while the two decision-makers were evaluating the hazard situation to select improvement alternatives. The decision-makers completed the improvement form.

Since all hazard data were recorded by one person, considerable time was saved because the recorder soon memorized the identification codes and necessary data for each type of hazard (in addition to the location on the form where these data must be recorded). It was evident that considerably fewer recording errors (omissions, erroneous codes, etc.) occurred when the data-recording operation was done by one person rather than rotating throughout the inventory team.

The confidence that may be placed on the analysis results is directly proportional to the confidence placed on the decision-makers' engineering ability to realistically assess the existing hazard and select viable alternatives. Since costs vary among wide-spread geographic locations and, indeed, within similar improvements in a localized area, the evaluation team members must be able to estimate improvement costs on an individual site basis. Since the safety recommendations made at the site influence the

analysis so heavily, it is important that a minimum of two decision-makers are involved in the on-site evaluation and subsequent remedial recommendations to avoid individual bias in the improvement process.

Location of Roadside Obstacles

Roadside obstacles are located with reference to existing roadway milepost signs or to points of known milepoint from the Road Inventory Log Sheets (such as a bridge or other structure that will remain in a fixed position). Sufficient accuracy may be obtained using a vehicle equipped with an odometer having a one-thousandth-of-a-mile recording sensitivity (approximately 5 ft.) and having data entry and bidirectional capabilities. The location process is discussed below.

The vehicle is stopped adjacent to a known milepoint and that mileage value is entered in the odometer. With the odometer set to record positively or negatively depending on the direction in which the inventory will progress (with or against roadway mileage markers), the vehicle is driven along the shoulder until a roadside hazard is encountered. The odometer reading is recorded as a point of reference on the vehicle (usually the front door of the vehicle) is adjacent to the beginning edge (upstream end) of the hazard. Figure 7 illustrates the method to locate a point hazard.
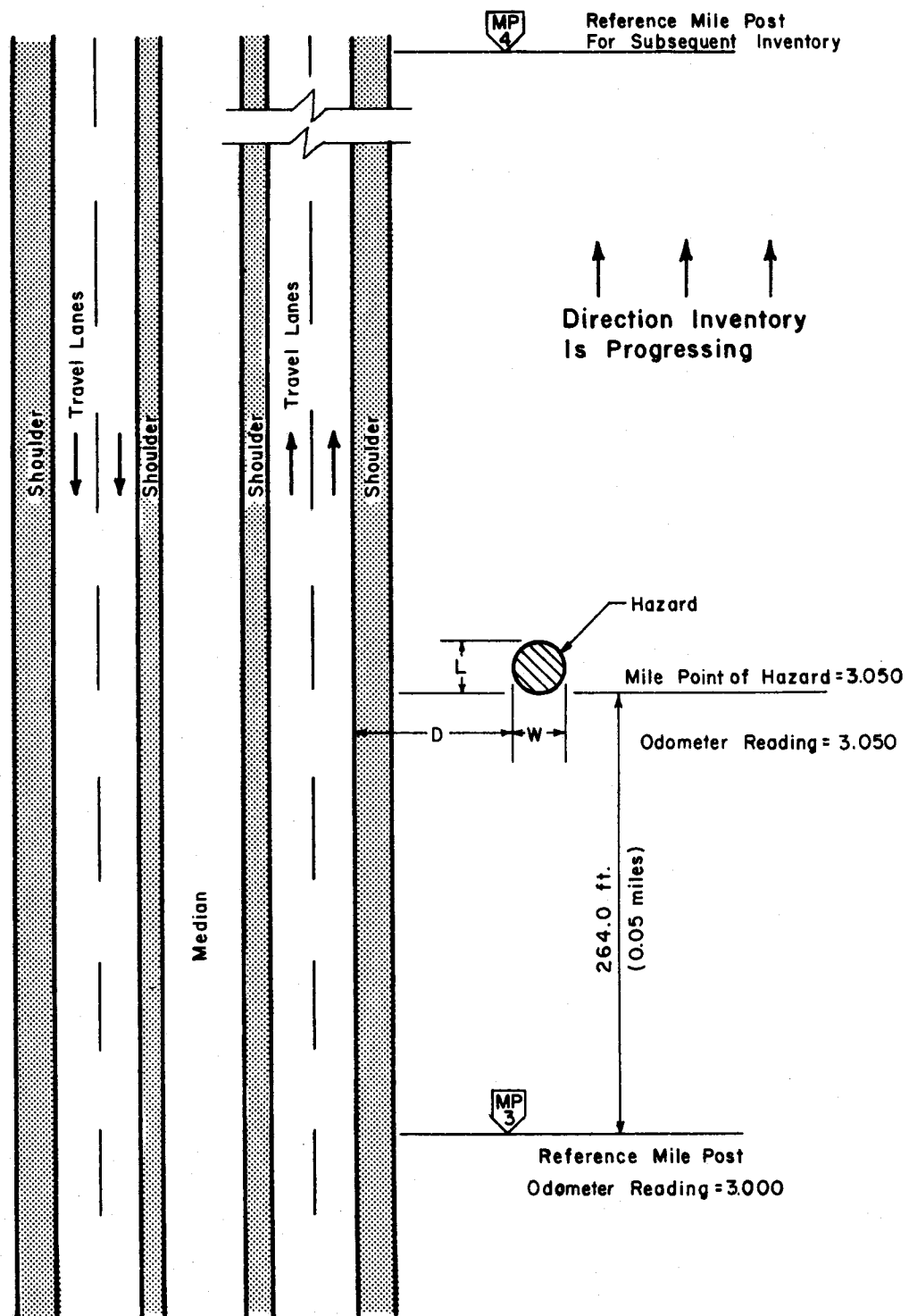
Figure 7.   Point hazard location and dimensions.

If the hazard is a longitudinal hazard such as a guardrail, the beginning point is located as above and the odometer reading is again recorded when the vehicle reaches the downstream end. The length of the longitudinal hazard is computed by the analysis program through subtraction. Figure 8 illustrates how a longitudinal hazard is located. The beginning and end points of a roadside slope are located in the same manner as those for a longitudinal hazard.

The odometer should be re-initialized frequently as points of known milepoint are passed; however, not within the extremities of a longitudinal hazard and never within the boundaries of a group of hazards. If a longitudinal hazard extends for an appreciable distance (such as a curb), it may be terminated at a point of odometer re-initialization and subsequently begun again at the same milepoint provided it is assigned a new hazard number. Techniques to accommodate these special cases are discussed in more detail later.

Roadside slopes 4:1 or steeper are included in the inventory, those flatter than 4:1 being considered non-hazards. The longitudinal length of a roadside slope for inventory purposes is defined as the distance between the point where the steepness first becomes 4:1 and the point at the downstream end where the slope ratio becomes flatter than 4:1, or terminates such as would be the case where the slope meets a cross-street under a structure. The end milepoint of a slope approaching an overcrossing structure may be considered to be the beginning point of the bridge rail.
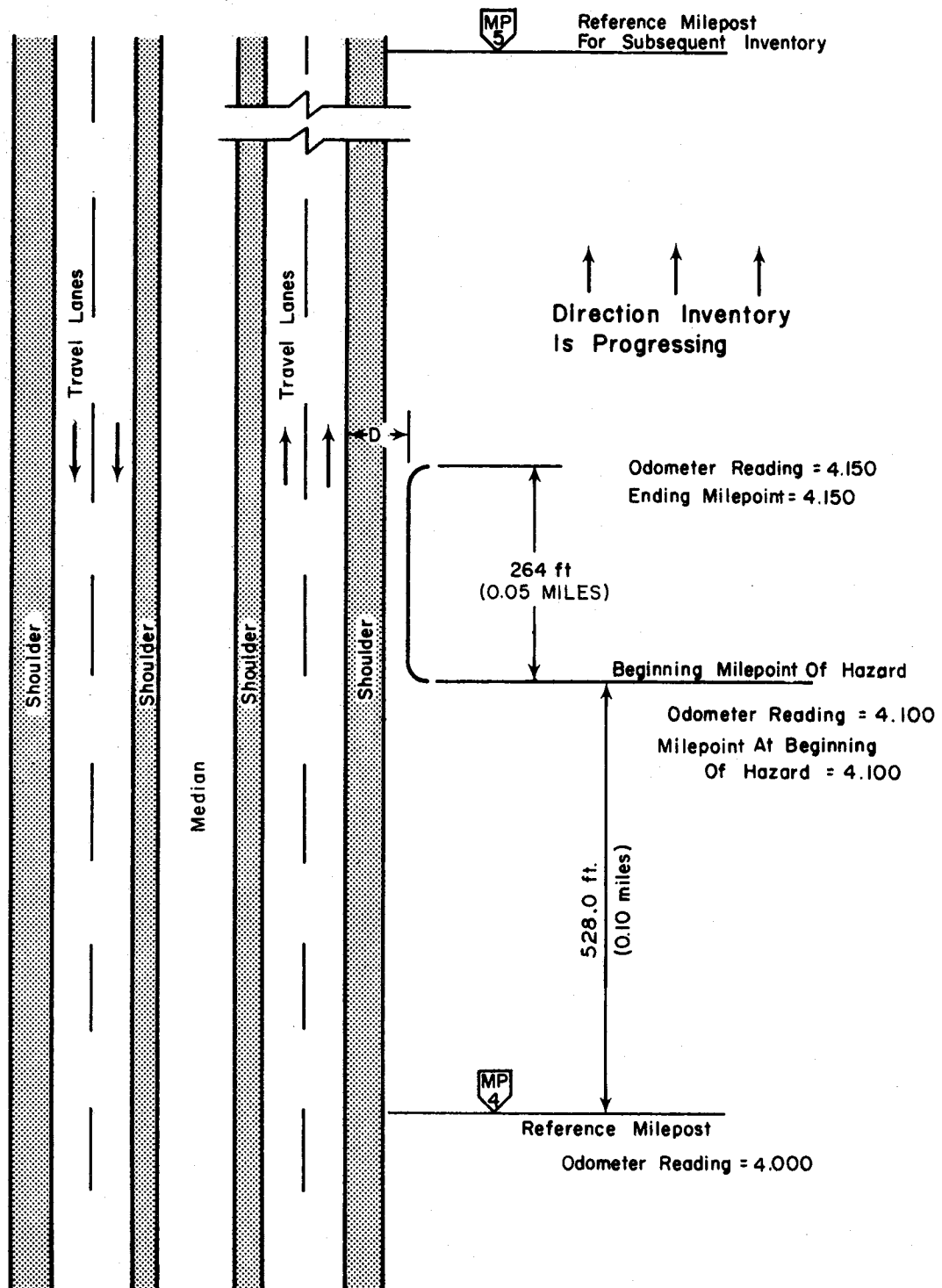
Figure 8. Longitudinal hazard location and dimensions.

58

Figure 9 illustrates the method of determining the beginning and end milepoints of a roadside slope approaching or departing a bridge.

Particular care must be taken in determining the longitudinal boundaries of long slopes having variable steepness. The average slope steepness over the slope longitudinal length is used in the analysis model. Therefore, to accurately define the slope geometry under severe steepness changes, the slope should be inventoried in sections, each being assigned a new hazard number. For example, a slope with a 4:1 beginning steepness, steepening to a 2:1 then flattening out again to a 4:1 should be inventoried as two individual slopes, the first ending at the 2:1 steepness and the second beginning at the same milepoint. If only the 4:1 slope steepness were recorded for each end of the total slope length, the average steepness would be calculated as 4:1 throughout the entire slope length and the slope hazard index computed on this value.

Several methods may be used to measure slope steepness. To alleviate the time-consuming operation of measuring slope steepness by conventional surveying techniques, a device called a "slope-ometer" was designed to permit rapid steepness measurement. This device consists of a steel ball that rolls within a 6-inch radius groove adjacent to a slope ratio scale. It is attached to a 3-ft. rod which is placed on the slope face and the slope ratio is read directly below the position at which the ball comes to rest in the
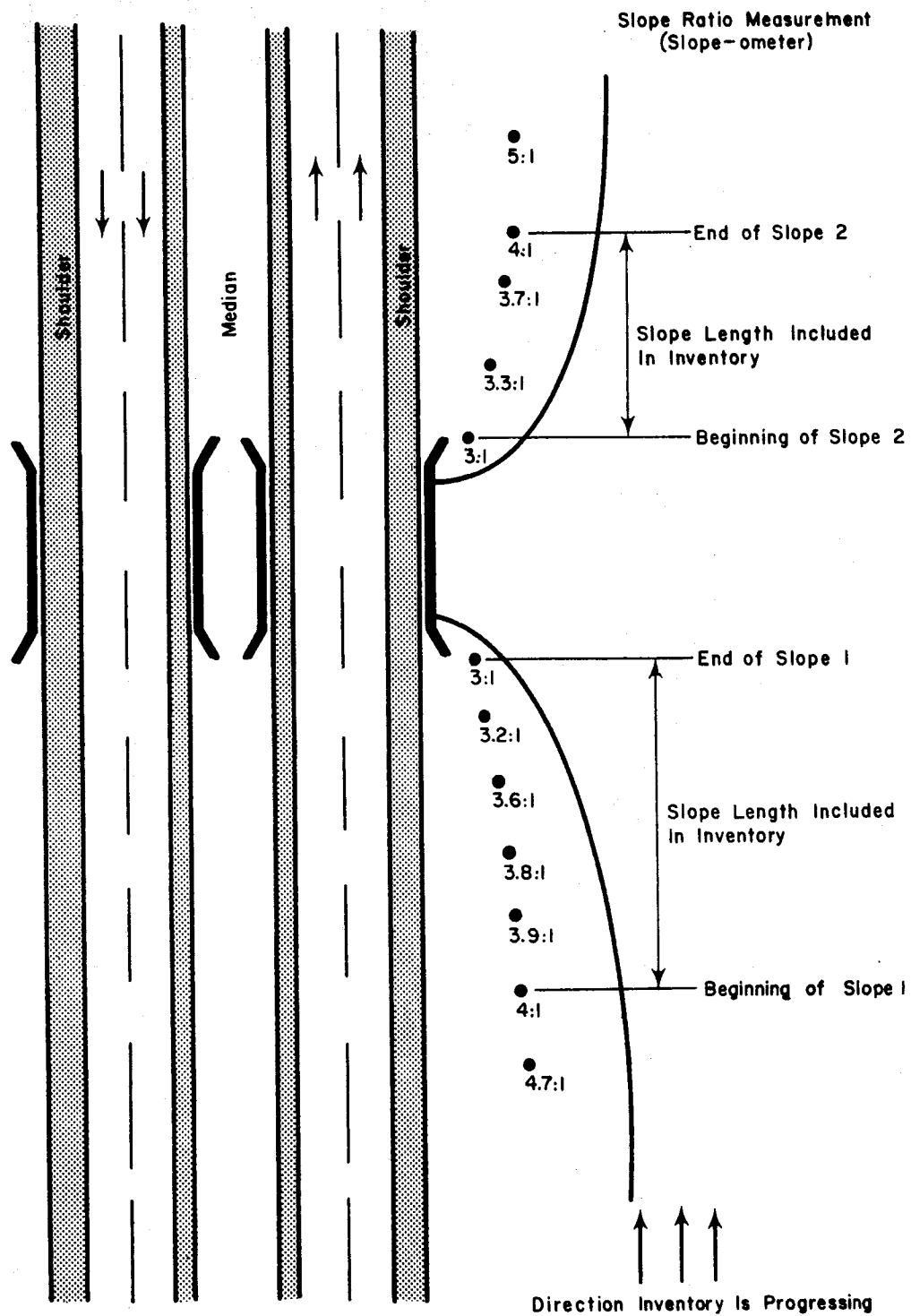
Figure 9. Determination of slope beginning and end points.

groove due to gravity.

Estimating the steepness of a roadside slope is difficult.
The slopeometer may be used to quickly determine if a slope is 4:1
or steeper and, hence, should be inventoried. Also, the beginning
and end milepoints of a slope may be quickly determined by a series
of measurements along the slope face as shown in Figure 9.

Completion of Hazard Inventory Form

Since the information recorded on the hazard inventory form
is transferred to computer cards, each entry on the form must be
recorded in a specific manner. Proper completion of the form is
discussed below. The five data blocks are discussed separately
and referred to by box number for identification purposes.

Highway Information (Box 1)

Contained in this category are general information concerning
the type and operating characteristics of the highway facility
under consideration; general location by county, control and sec-
tion, and inventory direction. These data are necessary for cross-
reference and information retrieval, but, more importantly, provide
basic decision-making information sources by which the computer
program operates.

The highway type (columns 1 and 2) coding numbers agree with
the codes used in the Road Inventory Log sheets (RI-1 sheets) to
facilitate cross-reference at a later date. Space is provided for

a four-digit highway number (columns 3 through 6) and highway numbers must be right-justified. For example, Interstate Highway 10 would be recorded as 08-0010 in columns 1 through 6, the 08 being the prefix code for Interstate Highway.

Access control classification (column 7) is defined by seven numerical codes. It is extremely important to the computer program operation that the proper codes be used for the particular highway being inventoried because the program branches internally on this code alone. Codes 1, 2, or 4 in Column 7 must be used when inventorying a median-divided highway. Codes 3, 5, 6, or 7 are applicable for non-median facilities. If codes 3, 5, or 7 are used, the roadway width from the center-line to the shoulder on the side of the roadway on which the hazard is located (columns 17 and 18) must be specified to the nearest foot. For codes 1, 2, 4, or 6, columns 17 and 18 may be left blank. The width specified in columns 17 and 18 is necessary within the program operation to calculate the additional hazard index of a roadside object to an opposing vehicle which can cross the undivided centerline and impact the obstacle from the opposite direction. If the width were not specified (resulting in a zero width), the additional increment would be in error.

The numerical code for the county in which the inventory is being conducted is recorded in columns 8-10. The alphabetical-numerical designation for counties used by the Texas SDHPT is incorporated in the analysis model with a cross-reference to the appropriate Texas SDHPT District.

The county number and District appear on all analysis output and may be used as a principal sort key for future sorting of data output.

The control and section number identification, used by the Texas SDHPT, generally is used more widely than the county or highway number. To facilitate cross-referencing hazard inventory forms to on-site location, space is supplied to record both control number (columns 11-14) and section number (columns 15 and 16). These data constitute a principal sorting key for computer analysis operations. Omission of these data or incompatibility between successive hazard coding (particularly within grouped hazards) will result in erroneous output.

Two other information sources necessary for program execution are included in Box 1; the total ADT on the facility (columns 19-21), and the recording direction (column 22). The ADT is used within the program to compute the probability of encroachment. In coding one way frontage roads (code 6, column 7) the total ADT for both frontage roads is used in Columns 19-21. Total ADT for each frontage road is used in coding two-way frontage roads (code 7, column 7). The direction in which the inventory is being conducted (with or against increasing milepoint) must be specified to direct the program to the proper operating routines.

Hazard Classification (Box 2)

The information in columns 23 through 38 is vital to the computer program for several reasons. It provides hazard description information from which severity indices are designated, provides

the key to direct the program to analysis of a rightside or median-located hazard, and is the information source to define a group of hazards rather than a single hazard.

Hazard number. The hazard number (columns 23-26) generally is assigned consecutively throughout the inventory section, beginning with number 0001. No two hazards within the same inventory length may be assigned the same hazard number. If additional hazards are inventoried after the initial inventory (or, if one was omitted), a new number must be assigned to the omitted hazard. The form may be inserted at the appropriate place within a sequence of inventory forms (say, arranged according to increasing milepoint) even though the hazard numbering sequence is thus non-consecutive.

Identification and descriptor codes. The identification and descriptor codes (columns 27-28 and 29-30 respectively) identify the type of hazard from which the severity index is assigned. Codes are shown in Table 1.

Offset code. The offset code (column 31) defines the position of the hazard with respect to the left or right side of the travel lane(s) in the inventory direction. A code 1 (right side) denotes that the hazard is located on the right side of the highway from the inventorying direction orientation. A code 2 (median or left side) is used when the hazard is located in the median on a divided high-way facility (either controlled or non-controlled access), or if the hazard is located on the left side of a non-median-divided

64

highway with respect to the inventory direction orientation.

Median width. The median width (columns 32-34) must be spec-
ified in certain situations, and not in others, as discussed below.
The median width should be left blank when an offset code 1 (right
side) is used. If the hazard is located in the median and the
median width is left blank, the hazard effect on opposing traffic is
not included in the hazard index determination. Under certain con-
ditions, this is satisfactory. For example, if the hazard were
located in a wide median near the left edge of the inventory travel
lanes and it was obvious to the person conducting the inventory
that an opposing vehicle would not cross the median and impact the
hazard, the additional increment of hazard index would be insig-
nificant. Therefore, the hazard should be inventoried as a near-
side median offset (code 2, column 31) and the median width left
blank (columns 32-34). The program would analyze the hazard
from an inventory-side impact only.

Also, on highways with wide medians (in excess of 60 ft.),
each set of travel lanes, in effect, operates as two independent
roadways. Therefore, each set would probably be inventoried in-
dividually; thus, the median width may be left blank.

There are, however, certain cases where the median width must
be recorded. If the effects of opposing traffic are to be consid-
ered, the median width must be specified. Also, if the entire
median is inventoried concurrently with one set of travel lanes,

65

the median width must be recorded. The median width is required if a hazard on the far side of the median (adjacent to the opposing traffic lanes) is inventoried from the inventory side, or if an improvement is recommended for the far side of the median.

It is recommended that the median width be recorded unless the inventory personnel are certain that the hazard should be considered only as a "near side" hazard; the term "near side" referring to the portion of the median adjacent to the travel lanes in which the inventory is progressing. If the median width is recorded for a situation in which it is not needed, it will not be used in the program calculations. Also, if the distance from the opposing lanes to the hazard is greater than 30 ft., yet the median width had been recorded, the hazard effect on opposing traffic would be determined by the program to be insignificant.

Grouping number. Of particular importance to the operation of the analysis program is the grouping number (columns 35-38). A "group" of hazards represents any two or more hazards in close proximity that are related to each other either by proximity or by interdependence in combined severity. For example, a guardrail protecting a point hazard on a slope constitutes a group of three hazards—the guardrail, the point hazard, and the slope. Each hazard within the 3-element group would be numbered individually, but the grouping number (columns 35-38) would be identical for all three.

The grouping number provides the only key to the program that

more than a single hazard is to be considered. Therefore, if an
improvement can affect any other hazard, that hazard must be in-
cluded in the grouping number. The only type of hazard that is not
considered part of a group is a single hazard. It is emphasized
that if the grouping number is omitted (or if a hazard is omitted
from a group), the program does not consider the improvement effects
on related hazards. Several basic premises apply to the use of
grouping numbers as discussed below:

1. A zero or blank grouping number is valid only for a
   single hazard;

2. The offset code (column 31) must be the same for all
   hazards within one group. Hazards on both sides of
   a highway cannot be grouped together--they must be
   inventoried as being in two separate groups;

3. If guardrail is included in a group, it is assumed
   that it protects the entire group. Therefore, any
   hazard that is not protected by the guardrail should
   not be included in the group;

4. If guardrail is included in a group, and improvements
   are recommended to hazards behind the guardrail, error
   messages will be printed out to this effect. There-
   fore, unless the guardrail is to be removed, all hazards
   behind the guardrail must be designated a "No Improve-
   ment" code. (Improvement recommendations are discussed
   later in this section.);

5. Generally, hazards within the median may be grouped
    together regardless of which set of travel lanes they
    are adjacent to. The primary exception to this occurs
    in inventorying the bridge-associated groups on both
    sides of a median. Each must be assigned a separate
    grouping number.

The grouping code is used at most overcrossing structures where
a typical group would include an approach guardrail, the bridge rail,
a departing guardrail, and a slope at each end of the structure.
These hazards normally exist both on the right side and on the
median side. A separate grouping number is assigned to the group
of hazards on each side (right side and median side) of the travel
lanes.

Many times, several individual point hazards will be spaced
close together. When clusters of point hazards of the same type
are encountered, they may be inventoried as a single point hazard
having dimensions of an imaginary box around their periphery. It
is recommended that bridge piers and small clusters of trees be
inventoried in this manner. Figure 10 illustrates a set of bridge
piers considered as a single point hazard. In effect, the in-
dividual piers act as a rectangular point hazard because a vehicle
cannot pass between adjacent piers. No grouping number would be
assigned in this case. Judgment must be used in clustering point
hazards as a single hazard, but a realistic criterion is that it
may be assumed to act as a single point hazard if a vehicle cannot
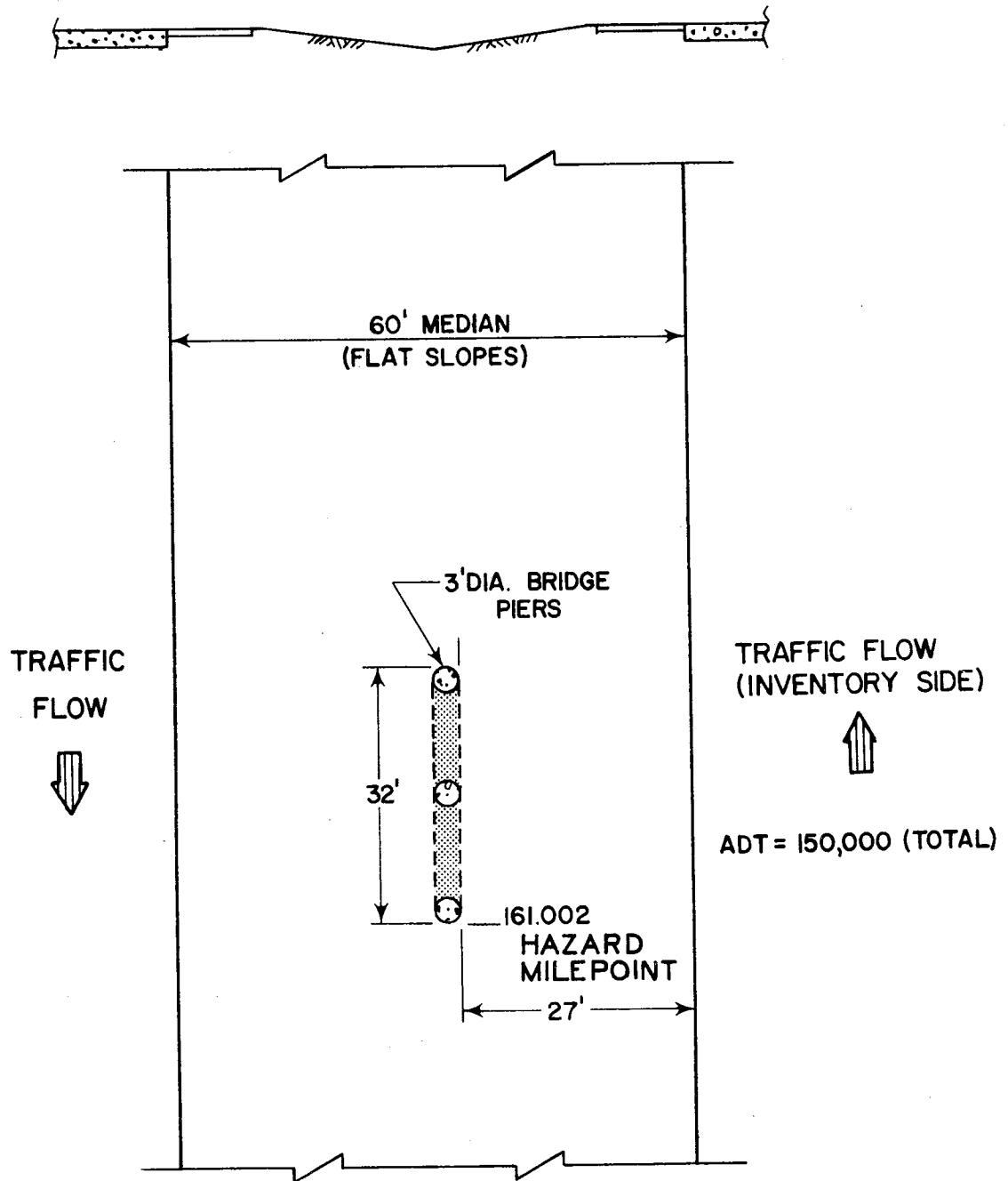
Figure 10.   Closely-spaced hazards inventoried as a single point hazard.

pass between any two hazards.

Figure 11 illustrates a series of hazards located in the median representing a grouping consisting of five individual hazards: (1) the guardrail, (2) a critical slope, (3) a cluster of three trees considered to be a point hazard with peripheral dimensions as shown by the shaded rectangle, (4) a raised inlet, and (5) a cluster of five trees again considered as a point hazard. Each of these five hazards would be assigned an individual hazard number and all would be assigned the same grouping number.

Milepoint at Hazard (Box 2)

All hazards are located along the highway by milepoint using the thousandth-reading odometer. It should be noted that only the beginning hazard milepoint is required for point hazards, but both beginning and end milepoints must be recorded for longitudinal and slope hazards, the length being computed by the computer program by subtraction of the two values.

It is again emphasized that Box 2 must be completed on each inventory form regardless of the category into which the hazard is assigned (Boxes 3, 4, or 5).

Point Hazards (Box 3)

The code 1 in column 51 designates that the hazard is a point hazard. With the exception of drop inlets, only hazard offset (columns 52-53), width (columns 54-56), and length (columns 57-59) are required in Box 3. All dimensions are recorded to the nearest
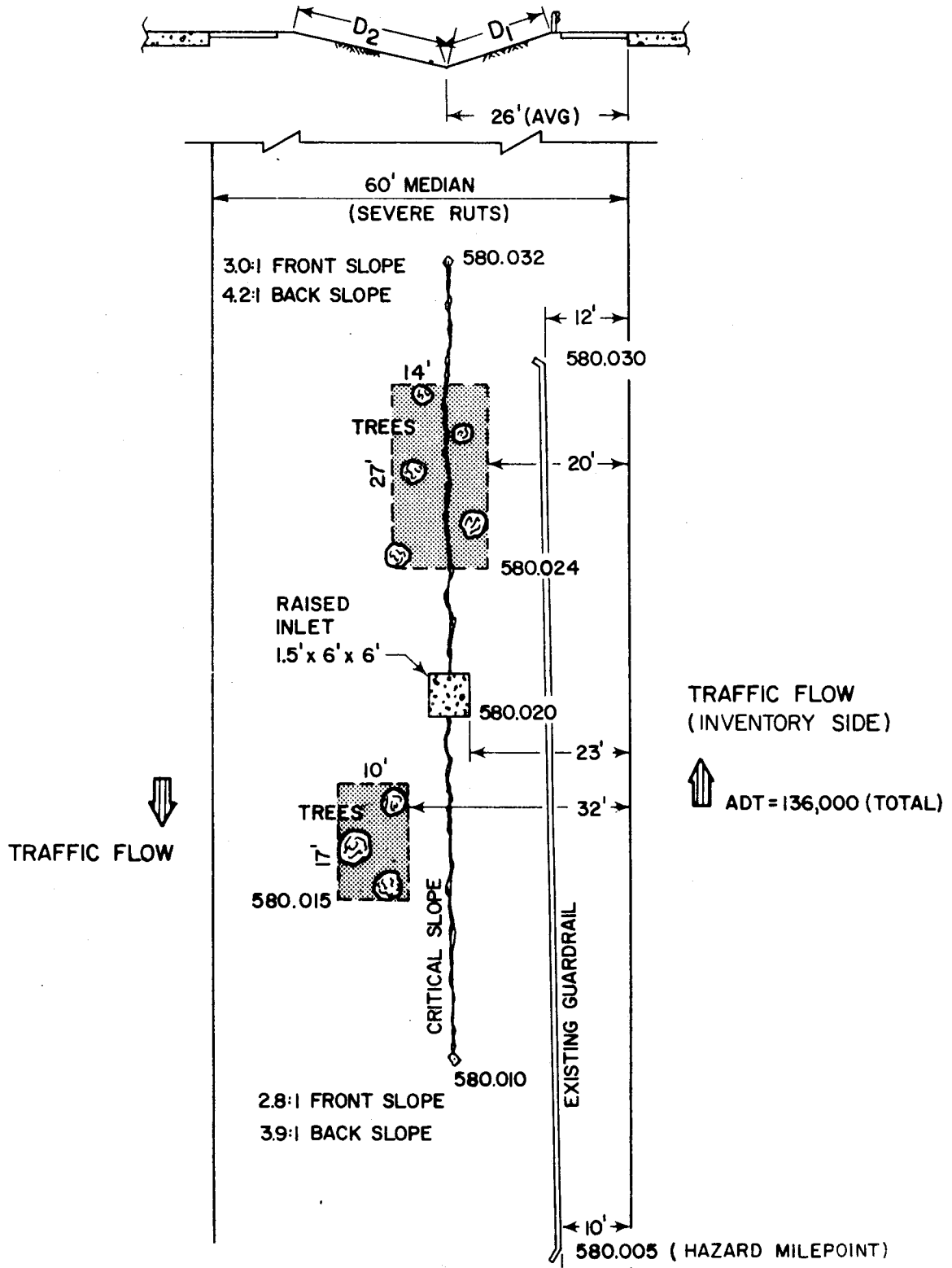
Figure 11.   Hazard grouping in median.

71

foot. In the case of a raised drop inlet (table top design), the height must be recorded (columns 60-62) to the nearest tenth foot. Similarly, for a depressed drop inlet, depth must be recorded in columns 63-65. These data are necessary to assign different severity indices for various heights or depths of inlets. For point hazards other than inlets, columns 60-65 are left blank. Point hazards are specifically identified in Table 1.

Longitudinal Hazards (Box 4)

Hazards assigned to this category include curbs, bridge rails, median barriers, guardrails, ditches, and retaining walls, and are so identified by the code 2 in column 51. The length of a longitudinal hazard is computed within the program from the beginning and end milepoint recorded in Box 2. Offset distance at the beginning and end of the longitudinal hazard is recorded in columns 52-53 and 54-55 respectively. In many cases, both offset distances will be identical because the hazard is located parallel to the roadway; however, provision must be made for the exception, and both offsets must be recorded. All dimensions for offset and width (columns 59-60) are recorded to the nearest foot. Height or depth (columns 56-58) must be recorded to the nearest tenth foot for guardrail, curbs, and ditches. Guardrail and curb widths (columns 59-60) are defined as 1 ft. The actual width for all other longitudinal hazards is recorded in columns 59-60.

Columns 61 and 62 pertain to guardrail primarily and identify end conditions and safety treatment; however, end treatment must

be specified for flex-beam median barriers also in these columns. Column 61 describes the beginning end; column 62 pertains to the downstream end. Four codes for each are provided, the sixteen combinations of which describe all possible guardrail installations. A guardrail may (1) be isolated (protecting a point hazard, a slope, or combination) and not connected at either end to a bridge or other structure, (2) be located at the approach to a structure, or (3) be located at the downstream end of a structure. Isolated guardrail may be safety treated including post spacing and end treatment in accordance with current accepted safety specifications, or it may not satisfy these specifications (not safety treated). Guardrail connections at bridge or other structure are classified as "full-beam connection" or "not full-beam connection." A full-beam connection is defined as one transmitting continuous rail strength through the "eight-bolt" connection or other connection assumed by the Texas Highway Department to be equally acceptable. All one-bolt connections, unconnected guardrail (short gap between rail and structure) and other such connections are classified as "not full-beam." Thus, an isolated guardrail installation of at least minimum length under current design standards, having current post spacing specified for safety, and turned down ends would be coded as a 1 (column 61), 1 (column 62). An approach guardrail with the beginning point safety treated, but connecting to a bridge wingwall with a one-bolt connection would be a 1, 4 code in columns 61 and 62 respectively.

Curbs on exit or entrance ramps are classified as longitudinal hazards and are inventoried rather uniquely. The length of the gore curb at an exit ramp is measured parallel to the main lane beginning at the nose of the gore area. If the highway is curbed throughout the region being inventoried, the length of the gore curb should be arbitrarily defined as 150 ft. and the subsequent curb inventoried as another hazard beginning at the arbitrary cutoff point. If only the exit region is curbed, the true length of the curb should be recorded. The width of the gore curb is defined as the average width of the gore at a point 25 ft. downstream from the gore nose, but not to exceed a width of 10 ft.

Guardrail height should be measured in all cases (columns 56-58). Also, each existing guardrail installation should be critically examined to determine if it is, in fact, protecting an object from impact for the 11-degree encroachment angle assumed in the model. The guardrail installation may meet all safety requirements yet be located such that an encroaching vehicle could pass either end and impact the object which the guardrail was intended to protect. This problem is especially prevalent where short sections of guardrail are installed to protect a point hazard, or at bridge approaches where a vehicle could travel behind the guardrail to encroach on a critical slope.

Slopes (Box 5)

Slopes 4:1 or steeper in the median and alongside the outer

74

travel lanes are included in the inventory and categorized as such by a code 3 in column 51. The hinge-point offset distance, D_0, must be specified for both ends of the slope (columns 52-55). Slope steepness (columns 56-59) is recorded to the nearest tenth for both beginning and ending milepoints.

To facilitate measurement of slope distances without elaborate surveying equipment, the distance, D_1, (columns 60-63) is measured. This distance is the length measured down the slope face from the hinge point to the toe of slope. Horizontal distance is computed within the program.

Space is provided (column 64) to record the degree of erosion on the slope face. In most cases, the code 1 (slight or no erosion) will be used, particularly if erosion cuts are present due to a recent rainfall, and normal maintenance would be expected to repair slopes. However, if erosion is severe (code 2), this fact should be noted. The program increases the severity index accordingly for badly eroded slopes.

The severity associated with slope traversal, other than vehicle rollover on a steep front slope, is actually dependent on the vehicle g-forces experienced as the vehicle travels through the region at the toe of slope. The combination of front and back slopes, therefore, influence the severity. To quantify this, the steepness of both front and back slope must be recorded. Space is provided in Box 5 to record similar data for both front and back slopes. The second slope may be either a back slope, or level

terrain such as might be encountered at the toe of a fill section. If the second slope is level terrain, the steepness (columns 66-69) and the distance D_2 (columns 70-73) should be recorded by a digit "9" in each space which is interpreted by the analysis program as being a level slope. The distance, D_2, is the length of the second slope measured from the toe to the hinge-point along the slope face. If the second slope is level terrain, D_2 should be recorded as 99 ft. at both end milepoints.

The slope direction (columns 65 and 75 for each slope respectively) is used to key the computer program to various subroutines for analysis purposes, and must be recorded. The slope direction convention is that used in roadway alignment—downward slope is negative (code 2); upward is positive (code 1). All direction codes are referenced to the plane of the roadway being inventoried. Level terrain at the bottom of a fill section is coded as a positive slope.

Figure 12 illustrates direction coding for several slope situations and is used to describe several "special" inventorying procedures for slope configurations. Two assumptions are made within the program to compute the hazard index, and the program keys on the value of slope steepness to select the appropriate analysis subroutine. This feature can govern the lateral distance that must be inventoried for a slope hazard as discussed below.

If the slope is flatter than 3.5:1, the assumption is made that the errant vehicle will recover within a lateral travel distance

CASE 1

FRONT SLOPE
(NEGATIVE SLOPE)
4:1 OR STEEPER

BACK SLOPE
(POSITIVE SLOPE)

CASE 2

ANY STEEPNESS

4:1 OR STEEPER

CASE 3

HINGE POINT

3.5:1 OR STEEPER

TOE OF SLOPE
HAZARD

SERVICE
ROAD

POSITIVE
ZERO SLOPE
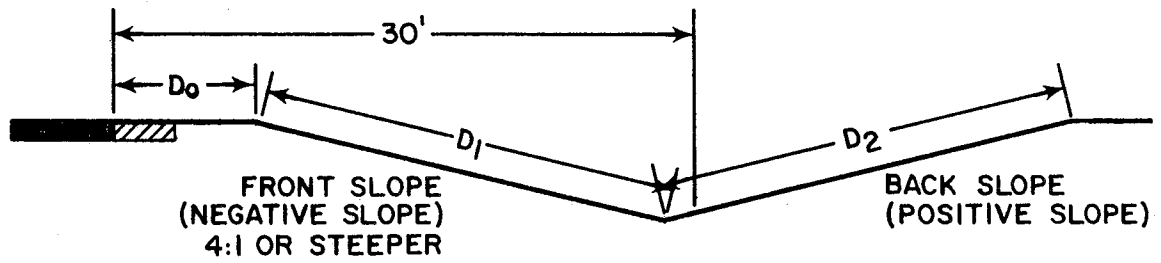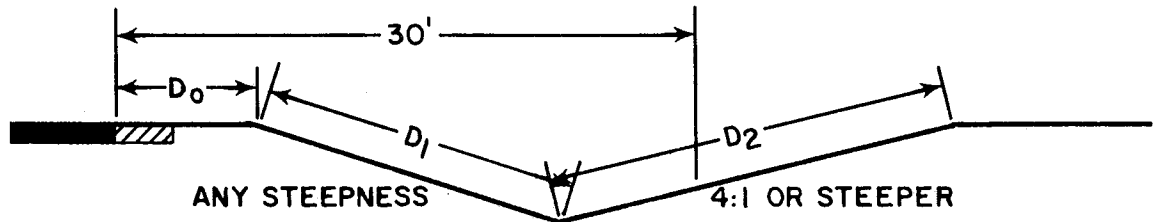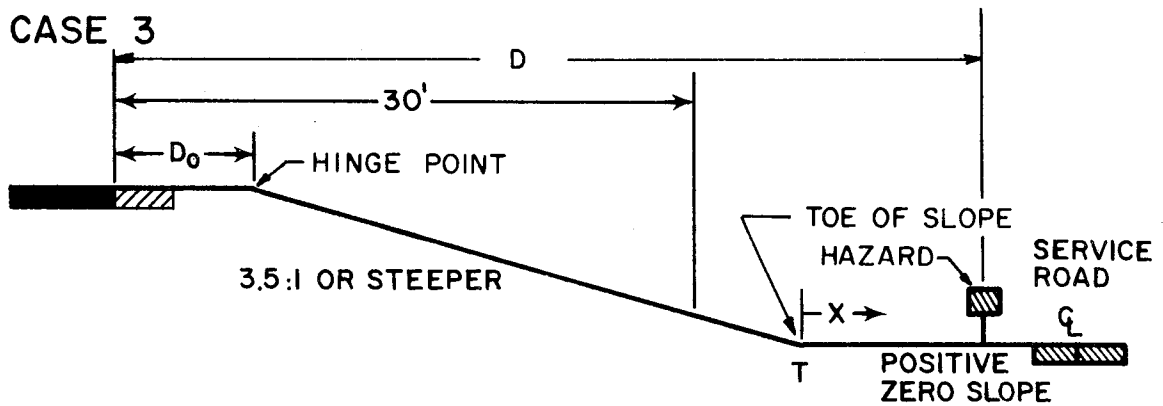
ALL HAZARDS LOCATED WITHIN $D_0 + X$ UNTIL 30'
TOTAL IS REACHED ARE INVENTORIED
OFFSET RECORDED FOR HAZARD = D.

Figure 12.   Roadside slope configurations.

77

of 30 ft. For slopes 3.5:1 or steeper, it is assumed that the ve-
hicle cannot be safely returned to the roadway and that it will
travel to the toe of the slope. Therefore, hazards located beyond
the toe-of-slope must be included if the sum of the hinge-point
offset distance to the front slope, D_0 (columns 52-55), and the
distance from the toe of the front slope to the hazard is 30 ft.
or less. Case 3 in Figure 12 illustrates the proper coding for
this situation.

Certain combinations of slopes can produce a situation in
which it is necessary to inventory a front slope flatter than 4:1.
If, for example, the front slope steepness was 5:1 and the back
slope steepness was 3:1, both slopes must be inventoried although
the front slope is flatter than the basic criterion of 4:1. The
severity index for the resulting ditch configuration is determined
by the vector difference in slope gradient; therefore, both must
be recorded to permit this calculation within the program. This
situation would be expected to occur infrequently within the
right-side 30-ft. lateral offset boundaries but becomes particularly
important when full-width median inventorying procedures are used
because of the increment of hazard associated with opposing traffic.
Case 2 in Figure 12 illustrates the situation.

When a long slope exists prior to a bridge structure, the
slope should be inventoried as two separate slopes--an isolated
slope and an approach slope--with the ending milepoint of one
being the beginning milepoint of the second. The arbitrary break-

78

point should be at least 150 ft from the bridge structure. This procedure must be used in cases where guardrail is existing or proposed for either slope because approach guardrail at a bridge is assumed to protect the approach slope rather than the bridge end wall. This is discussed in more detail later.

Card Type

Hazard inventory data are key-punched on a computer card designated by a code 1 in column 77. Each inventory card must contain this coded information for proper input information in the computer program.

Recommendations

Space is provided at the bottom of the inventory form to specify the improvements to the hazard. This information is not key-punched, however, it is useful in manual checking coded information using the field-completed form. It is recommended that each improvement alternative be noted on each inventory form. This, in conjunction with the general hazard description in the upper right corner of the form, provides a concise explanation of the existing hazard and recommended improvements.

Completion of Hazard Improvement Form

The hazard improvement form provides the mechanism by which the recommended safety improvements are coded for analysis input. An improvement form must be completed for each hazard inventoried.

The manner in which improvement alternative information is input to the program is equally as important as the inventory data input. The way in which the improvement form is used is discussed in the following paragraphs.

Location and Cost Information (Box 1)

The hazard number (columns 1-4) entered on the improvement form must agree with the hazard number on the applicable inventory form. Similarly, the location information (columns 5-17) must be identical on the inventory and improvement forms. Incompatibility of these data will produce error messages in the output because the link between existing hazard and improvement is provided to a large degree by this row of data.

The cost-effectiveness analysis model operates on the principle of severity-cost relationship of the existing hazard compared to the same relationship in its improved state. Therefore, costs must be assigned to both conditions. Costs are defined as those which will be borne by the agency conducting the safety improvement program. They do not include vehicle damage or personal injury costs incurred in a collision.

The "first cost of improvements" (columns 18-23) represents the initial lump-sum net cost associated with incorporating the improvement. It may represent a cost of removal if simple removal was the recommended safety improvement. Where installation of guardrail was the recommended improvement, it would represent the total cost

associated with this installation.

Repair costs per collision (excluding vehicle repair costs and personal injury costs) must be estimated both for the existing hazard (columns 24-27) and the recommended improvement (columns 28-31). Either may be zero, depending on the particular hazard. For example, repair cost per collision incurred by a collision of a vehicle with a bridge pier would be zero unless the collision involved a large truck and the pier was severely damaged structurally. The repair cost for the improvement, had protection by a barrel attenuation device been recommended, would be the expected replacement costs for the damaged barrel system after collision. Conversely, the hazard repair cost for a rigid sign post may be complete replacement cost of the sign, whereas a recommendation of "removal" would reduce the expected improvement repair cost to zero since future collisions would be impossible at that location.

Normal maintenance costs include those maintenance costs for the hazard in its existing state (columns 32-35) and those estimated for the improved state (columns 36-39). As was the case for repair costs, either could be zero. If the recommended improvement was removal, the "improvement normal maintenance costs" would be zero.

In all cost data spaces, zero should be entered where applicable rather than merely leaving the space blank. This acts as a check system to avoid overlooking data spaces. All data spaces in Box 1 must be completed on each hazard improvement form to avoid rejection of the total data by the computer program. Each line of

data checked should be completed fully unless otherwise noted.

Point Hazard Improvements (Box 2)

A code 1 in column 40 signifies that the improvement applies to a point hazard. Four improvement alternatives are available with the appropriate codes entered in column 41.

Alleviate hazard (code 1, column 41). This code includes removal, making the hazard breakaway, reconstruction of the hazard to a traversable design. The particular subdivision is identified by a code 1, 2, 3, or 4 in column 42.

Protect hazard with guardrail (code 2, column 41). This code may be used for any point hazard that is not located on a slope. The lateral offset must be specified in columns 42-43 if the guard-rail is recommended for a hazard on the right side or median near side. If guardrail is specified on the median far side, (median must be inventoried across full width), the offset (measured from inventory side to front face of far side guardrail) must be entered in columns 44-45.

Clusters of hazards of the same type such as several signs or several trees may be protected by guardrail as a unit. The periph-eral boundaries of the cluster are used to define the hazard dimen-sions. Bridge piers should be inventoried in this manner.

<u>Protect hazard with concrete median barrier (code 3, column 41)</u>.

A concrete median barrier may be recommended for either the median location or on the right side. If the barrier is placed in the median, the offset distance need not be specified since the dimensions relative to the hazard are built into the computer program. If the barrier is recommended for right-side placement, the offset distance (columns 42-43) must be specified. A 35-ft. length of median barrier both upstream and downstream from the point hazard is assumed in the analysis program. Therefore, length need not be specified on the improvement form.

<u>Protect hazard with energy attenuation system (code 4, column 41)</u>. When this improvement is recommended, length (columns 42-44), width (columns 45-46) and offset distance (columns 47-48) must be specified. If, for example, a barrel attenuation system is recommended to protect a median bridge pier, the length of only one barrel system is specified. Similarly, costs for only one system are entered. If the median was inventoried only for near-side, the analysis of the improvement is based only on an impact from the inventory side. However, if the median width is specified, the analysis is based on an opposing impact also and the program determines if two attenuation systems are indeed required (one at each end of the piers) to protect the piers from both directions of traffic flow. If two systems are required, the cost-effectiveness

83

index is computed on the double system and costs are doubled internally although dimensions and costs entered on the improvement form reflect only a single system. The data output will reflect the double costs.

Longitudinal Hazard Improvements (Box 3)

A code 2 in column 40 identifies the improvement as a longitudinal improvement. Improvement alternatives are provided for four types of longitudinal hazards:

        1. curb (code 1, column 41);

        2. bridge rail (code 2, column 41);

        3. guardrail (code 3, column 41); and

        4. ditch (code 4, column 41);

each having several sub-categories as denoted by a code in column 42. The bridge rail category is further subdivided by codes in column 43.

In certain sub-categories, completion of Box A or Box B is required. These data spaces need to be completed only when the appropriate instruction appears adjacent to the selected improvement alternative on the improvement form. Box A pertains only to installation of a longitudinal improvement where none existed previously such as the installation of new guardrail, approach or departing guardrail at bridges, or lateral relocation of a bridge rail if the bridge is widened. When only minor modifications are made to ex-

isting longitudinal hazards (examples: lengthening, shortening, or closing up gaps between existing guardrail sections), Box B must be completed. It should be noted that a guardrail may be lengthened (Box B) in three ways: (1) adding guardrail to the beginning end (columns 43-46); (2) adding guardrail to the downstream end (column 47-50); or (3) adding length to both ends (columns 43-46 and 47-50). Similarly, guardrail may be shortened in the same ways (columns 51-58). Gaps between consecutive guardrail sections may be closed up by lengthening either the upstream or downstream section by the gap length.

Extreme care should be exercised when completing Box A to assure that entrees are properly located. Approach guardrail at a bridge must be coded in columns 44-47 and departing guardrail must be coded in columns 48-51. If, for example, approach guardrail were coded erroneously in columns 48-51, the information needed for program operation would not be provided to the computer program.

Curb. Two improvement alternatives are provided for curbs, each being identified by a code in column 42.

Bridge rail. Four improvement alternatives are provided (column 43) for each of two recommended bridge rail types (column 42). "Upgrade to full safety standards" (code 1, column 43) is interpreted to include all safety improvements necessary to bring the existing rail up to the highest current safety standards.

This may include only minor anchorage modification, or it may include complete replacement of the existing rail with a new rail system. The costs associated with the improvement will reflect the degree of construction necessary.

If the recommendation is made to move the rail laterally (code 3, column 43), bridge widening would be necessary. Again, costs will reflect the degree of construction necessary to accomplish this alternative. As noted on the improvement form, Box A must be completed to designate the offset distance for the proposed bridge rail.

Installation of guardrail across a bridge rail face (code 3, column 43) represents a safety improvement that is being incorporated on many bridges. This feature provides continued beam strength across the bridge in addition to reduced severity of collision with the concrete bridge rail face. Although it constitutes rather major reconstruction, provision is made to evaluate the safety improvement of decking over the gap between parallel bridges (code 4, column 43). Box A must be completed if this alternative is selected.

Guardrail. Six safety improvement alternatives are provided for guardrail hazards, each identified by a code number in column 42 under the guardrail general codes 2 and 3 in columns 40 and 41 respectively. In most instances, guardrail will be inventoried as a part of a grouping because it invariably is installed to protect

some other hazard, either a point hazard, a longitudinal hazard, or a slope. Therefore, care must be taken in the improvement recommendation to insure that all hazards within the group are accounted for in any recommendation involving guardrail removal. Indiscriminant removal of guardrail will expose hazards located behind it (and, therefore, previously inaccessible to vehicle impact) so that they now become potential hazards.

Guardrail installation procedures according to Texas Highway Design procedures are incorporated into the computer analysis program. Therefore, when new guardrail is recommended, its placement and minimum length to protect a point hazard or a group of point hazards will be in accordance with these specifications. The minimum length of guardrail installation is 150 ft. not including safety treatment at the upstream end and required overlap at the downstream end of the hazard.

It is emphasized that approach and departing guardrail at bridges are not included as a "guardrail" improvement in the longitudinal hazard improvement category. Approach and departing guardrail at bridges are treated as slope improvements and are discussed in that category later in this section.

Removal of existing guardrail is accomplished by using a code 1 in column 42. Since the improvement form is keyed to the inventory form by hazard number, and Texas Highway Department guardrail specifications are built in, no longitudinal dimensions are required on the improvement form. Removal is defined as complete removal of

the total length of guardrail inventoried.

Full safety standards for guardrail include safety treatment of ends, current post spacing (6 ft.-3 in.) and height in accordance with latest safety specifications, and full-beam connections at bridge ends if the rail attaches to a structure. If this recommendation is selected, a code 2 is placed in column 42. Where additional length must be added to provide the 150-ft. minimum allowable length, Box B must be completed. This code is not used when only closure of short gaps is recommended; a separate code (code 4) is used for this purpose.

When gap closure is required in addition to upgrading (post-spacing, end treatment, etc.), a code 3 is placed in column 42 and Box B is completed. Cost entries would reflect the total improvement cost.

A code 5 in column 42 is used when only the anchorage connection of guardrail attaching to a bridge is recommended (no other upgrading of the guardrail is necessary, or recommended). A separate code is provided (code 6) to recommend safety treatment of only the free-end portion of guardrail located at either end of a structure. It is noted that this code applies only to the free end of guardrail beginning or terminating at a structure, not to isolated guardrail protecting a hazard that is not associated with a structure. Use of the code 6 implies that only the end point of the rail furthest from the structure will be safety treated (turned down, buried, anchored, etc.) and that no changes will be

made to existing post spacing other than perhaps at the treated section.

In all cases where installation of new guardrail is recommended, it is assumed that the new installation will comply with the highest current safety specifications and costs must reflect this.

Ditch. Three options are available for safety improvements recommended for ditches. Ditches under the "longitudinal hazard" category, include both longitudinally or laterally oriented ditches caused by erosion (washout) or designed ditches to carry runoff along or down fill slopes such as are often found near overpassing structures. Ditches formed by the intersection of roadside slopes are not included in this category and are not coded as an individual hazard. Instead, provision to evaluate the severity of this feature is incorporated in the front and back slope categories in Box 5 on the inventory form and Box 4 on the improvement form.

Slope Improvements (Box 4)

Three possible recommendations may be made with respect to slopes. First, the slope may be left in its existing state without guardrail protection. Guardrails may be recommended to protect the slope. Finally, a slope or combination of front and back slope may be regraded to a flatter cross-section such that an errant vehicle can safety traverse it. The latter recommendation, of course, constitutes rather major reconstruction. However, it is emphasized that slope flattening and drainage inlet changes may constitute a

very cost-effective safety improvement and should not be overlooked as a feasible improvement alternative. Investigation of this alternative through the cost-effectiveness model alleviates personal bias toward this improvement alternative.

For purposes of differentiation on the improvement form, slopes are classified in two basic categories--isolated slopes not beginning or terminating at a bridge; and slopes adjacent to a bridge. Improvement alternatives include installation of guardrail or flattening the slope for the isolated slope; guardrail only for the slope adjacent to a bridge.

Slope improvements are denoted by a code 3 in column 40 with the four subcategories of improvement denoted by the appropriate code in column 41.

Guardrail protection for an isolated slope is specified by a code 1 in column 41. This option is applicable for slopes with or without point hazards. The guardrail offers protection for the entire group of hazards. Since new guardrail is recommended where none existed previously, Box A must be completed with this improvement alternative.

Installation of approach or departing guardrail at a bridge is coded as a slope improvement by a code 2 in column 41. Although it generally is accepted that approach guardrail offers protection from an exposed wingwall in addition to the steep slopes normally found adjacent to a bridge, the computer program logic is based on the slope protection rather than the point hazard protection of the

bridge end. Therefore, a slope adjacent to the bridge must be inventoried as part of a hazard grouping for this improvement alternative. It is highly improbable that a slope would not exist near a bridge; however, if one does not, a "dummy" slope with an arbitrary steepness and other necessary dimensions to define the "dummy" slope must be included in the hazard grouping. Suggested "dummy" slope data are as follows: 150-ft. length, 4:1 front slope, level second slope, 10-ft. front slope hinge-point offset.

It may be desirable to install continuous guardrail between closely spaced bridges, particularly on non-controlled access roadways. This improvement may be accommodated by a code 3 in column 41, with successive bridges and the slope between them being treated as a hazard grouping. Each side of the roadway must be treated as an individual group.

The hazard associated with traversing a slope is dependent primarily upon two factors: the steepness of the front slope, and the relative difference between steepness of front and back slopes. The cross-section of the ditch formed between front and back slopes also influences the vehicle g-forces; however, the severity indices incorporated in the computer program are based on a vee-ditch.

Therefore, in recommending a slope flattening, both front slope steepness (columns 46-49) and back slope steepness (columns 55-58) must be specified. If the back slope is level terrain, it is assigned a steepness of 9.9:1 in columns 55-58. The distance, D_1, (columns 50-53) which is the distance from the hinge-point to toe-

of-slope along the slope face, must be estimated because until detailed cross-section data are prepared, the toe-of-slope for the newly proposed slope will not be known. The distance, D_2, for the second slope also must be estimated. If the hinge-point offset for the proposed front slope does not differ from the existing slope, the entry in columns 42-45 will be identical to the hinge-point offset of the inventoried slope. If the hinge point is expected to be moved laterally, the new offset must be estimated and entered in columns 42-45. The slope direction code must be entered for both the front and the back slope in column 54 and 63 respectively.

If only a portion of a slope is to be flattened, provision is made to enter the beginning milepoint (columns 64-69) and ending milepoint (columns 70-75) for the boundaries of the improved (flattened) section of the slope. If the entire slope is to be flattened, these spaces are left blank.

No Improvement Recommended (Box 5)

The computer analysis program is developed on a specific relationship between hazard inventory and hazard improvement. Although more than one improvement form may be provided for each hazard inventory form, the basic requirement must be met. That is; for each hazard inventoried, there must be at least one corresponding improvement recommendation even if the recommendation is one of "no improvement." Provision for this is made through a code 4 in column 40 on the improvement form. Some examples are discussed to

illustrate the use of this code.

Many times a group of hazards is inventoried in which guardrail is protecting one or more hazards. Each individual hazard within the group must be inventoried. If the safety improvement recommendation for the whole group is that only the guardrail be upgraded to full safety standards and nothing be done to the hazards behind the guardrail, the improvement for each of the hazards behind the guardrail would be merely a code 4 in column 40. If guardrail exists in a group, it is assumed to protect all hazards behind it. Therefore, improvement to any hazard behind it must be a code 4 in column 40 unless guardrail removal is recommended as the improvement alternative for the guardrail. If guardrail removal is recommended, the hazards behind it then become open to vehicle impact. Also, guardrail must be inventoried as a hazard grouping--it cannot be inventoried as a single longitudinal hazard protecting no other hazard. Therefore, it is strongly recommended that every hazard be inventoried. If at a later date, the guardrail is removed, the group evaluation would be incomplete because no data would be available concerning objects located behind it. Also, reasons other than safety evaluation may require a detailed inventory of particular hazard types along a section of highway and retrieval programs could be adapted to locate the information from the inventory data.

The "no improvement" code is not intended to be used as a "catch-all" for these hazards which appear to have no feasible

improvement possibility. It is provided to reduce the field time required in completing the forms while maintaining the computer program requirements that an improvement form be provided for each hazard form. If an improvement form is not provided, an error message will be printed out on the data output.

Card Type

Hazard improvement data are key-punched on computer cards designated by a code 2 in column 77. Each improvement card must contain this coded information for proper input information in the computer program.

Analysis Model Usage

Model Capabilities

The model is capable of evaluating 4 improvement alternatives for a single hazard, or a hazard grouping containing a maximum of 15 hazards with 4 improvement alternatives per hazard. Four alternatives were ample in all cases during field testing; in only rare instances were more than two alternatives required.

Data Input

Correct type, location, and amount of data on an inventory or improvement form are imperative for successful operation of the computer analysis program. It is equally important that the data deck be correctly arranged so that an equal number of improvement alternatives are provided for each hazard within a hazard grouping.

In any hazard/improvement set, the improvement card (or cards) follows immediately behind the hazard card to which it applies. A maximum of four improvements is allowed per hazard. Particular care must be exercised in arranging the sequence of improvement cards within a grouping because the improvements are evaluated in a prescribed sequence. For example, using Figure 13 to illustrate, in the grouping of 3 hazards with 2 improvement alternatives, the analysis procedure for the first improvement considers improvement alternative 1 with the first hazard, alternative 1 with the second hazard and alternative 1 with the third hazard as a single group evaluation. A group cost-effectiveness is computed. The process is then repeated using improvement alternative 2 with each of the three hazards and a group cost-effectiveness is again computed. Therefore, compatible alternatives must be in the proper sequence throughout the group deck arrangement.

Since a group cost-effectiveness is computed in the above described manner, it should be noted that within each group, the same number of improvement alternatives must be specified for each hazard, even if for one hazard in the group, a "No Improvement" alternative is recommended. For example, if in a three-hazard grouping, two improvement alternatives are recommended, two improvement alternative cards must be inserted behind each of the three hazard inventory cards. If two improvement alternative cards were inserted for the first two hazards and only one for the third hazard, the omission error would be detected during data reading, and no computer

95

SINGLE HAZARD
3 IMPROVEMENT
ALTERNATIVES

IMP. ALT. 3

IMP. ALT. 2

IMP. ALT. 1

HAZARD

Single Hazard

3 HAZARDS IN GROUP
2 IMPROVEMENT ALTERNATIVES

IMP. ALT. 2

IMP. ALT. 1

HAZARD

3rd Hazard in Group

IMP. ALT. 2

IMP. ALT. 1

HAZARD

2nd Hazard in Group

IMP. ALT. 2

IMP. ALT. 1

HAZARD

1st Hazard in Group

SINGLE HAZARD
1 IMPROVEMENT
ALTERNATIVE

IMP. ALT. 1

HAZARD

Single Hazard

JCL
CARD DECK

NOTES :

1. MAXIMUM NUMBER OF HAZARDS PER GROUP = 15

2. MAXIMUM NUMBER OF IMPROVEMENT ALTERNATIVES = 4 PER HAZARD

3. NUMBER OF IMPROVEMENT ALTERNATIVES MUST BE EQUAL FOR EACH HAZARD IN GROUP

Figure 13.   Arrangement of input data cards.

execution would occur on either of the two improvement alternatives even though the error applied only to the second improvement alternative. An error message, therefore, would be printed on the output data and no group cost-effectiveness would be computed for either improvement alternative.

Error Messages

Since computer program execution is highly dependent on precise data input both in type and location, error messages have been incorporated into the program to identify input errors. Due to the complexity of the program and extensive branching within subroutines from several data sources, it is expected that data input errors will occur. To avoid program termination (which would normally occur for each data error), the program has been developed to bypass the erroneous data, print out an error message, and continue with the next data input.

The fifty-one error messages shown in Table 4 have been incorporated. The list of numbered messages is printed out for each computer run, and each error message occurring is identified in the data output by reference number. Also printed out is the location within the program or subroutine in which the data error affected the program execution. The message indicates the type of error and provides direction to remedy the data error. The program will automatically terminate if 100 error messages are printed during any run.

TABLE 4

LIST OF ERROR OR FLAG MESSAGES

Message Number	Subroutine Calling Message	Description of Message
1	HAZARD	End milepoint at hazard not specified
2	PTHAZ	Unmatched point hazard and improvement codes
3	PTHAZ	Non-existing improvement classification specified in column 41 of improvement form
4	DITCH	Non-existing ditch improvement code classification
5	RAILNG	Guardrail installation not necessary--re-examine roadway group hazard
6	HAZARD	Non-existing hazard classification specified in column 51 of inventory form
7	PTHAZ	Non-existing point hazard improvement code (column 40)
8	PTHAZ	No improvement needed, flat slopes and/or offset greater than 30 ft (right side or median near side)
9	PTRAIL	Distance between guardrail and obstacle less than 3.0 ft
10	LGHAZ	No improvement needed, flat slopes and/or offset to longitudinal hazard > 30 ft (full median)
11	CURB	Non-existing curb improvement classification specified in column 42 of improvement form
12	BRIDGE	Non-existing bridgerail improvement classification specified in column 42 of improvement form
13	BRIDGE	Non-existing bridgerail improvement classification specified in column 43 of improvement form

TABLE 4 . CONTINUED

Message Number	Subroutine Calling Message	Description of Message
14	RAIL	Non-existing guardrail improvement classification specified in column 42 of improvement form
15	RAIL6	Guardrail end-treatment adjacent to bridge incorrectly specified
16	LGHAZ	Longitudinal hazard offset on non-critical slopes greater than 30 ft (right or median near side)
17	SLOPE1	Non-existing slope direction classification specified on inventory form
18	LGHAZ	Curb improvement valid only for curb hazard
19	ZERO, DITCH	Logic breakdown--vehicle not permitted to penetrate guardrail
20	PTHAZ	No improvement needed, flat slopes and/or offset greater than 30 ft (median inventoried across)
21	ZERO	Logic breakdown in subroutine ZERO--refer to flow charts
22	PTHAZ	Point hazard offset greater than 30 ft on right or median near side (critical slopes)
23	MAIN PROGRAM	Stop computer program -- 100 or more errors
24	HAZARD	Unmatched identification information
25	LGHAZ	Bridgerail improvement valid only for bridgerail hazard
26	LGHAZ	Guardrail improvement valid only for guardrail hazard
27	INVTRY	End of data and program

TABLE 4 CONTINUED

Message Number	Subroutine Calling Message	Description of Message
28	HAZARD	Unequal number of improvement alternatives per hazard in group
29	RAIL1	Not permitted to remove 1 guardrail on median side if other guardrail on same side is not removed
30	MAIN PROGRAM	*Hazard improvement not cost-effective*
31	HAZARD	Hazards on right side and left side of roadway cannot be grouped together
32	HAZARD	Guardrail end treatment code not specified on inventory form
33	HAZARD	Guardrail end treatment code not defined-- value greater than 4.
34	HAZARD	Improvement costs not specified
35	HAZARD	Guardrail hazard repair and/or maintenance costs not specified
36	HAZARD	Guardrail improvement repair and/or maintenance costs not specified
37	LGHAZ	Longitudinal hazard offset greater than 30 ft (critical slopes) on right or median near side
38	ZERO	Logic breakdown in guardrail consisting of point hazards and guardrail on both sides of median
39	ZERO	Improvement not needed for existing point hazard behind existing guardrail
40	----	Reserved for future use
41	BRIDGE	Median inventoried across width allowed only for improvement codes 2 or 4 in column 43

TABLE 4 CONTINUED

Message Number	Subroutine Calling Message	Description of Message
42	DITCH	Ditch improvement not needed behind existing guardrail
43	LGHAZ	Ditch improvement valid only for ditch hazard
44	BRGR	Approach and departing guardrail offsets not specified in columns 44 through 51
45	LGHAZ	Non-existing improvement classification specified in column 41 of improvement form
46	DTRAIL	Median inventoried across full width but no guardrail specified to protect far side
47	SLHAZ	Slope improvement not specified in columns 40 or 41 on improvement form
48	SLRAIL	Inventory median full width only if guardrail also needed on far side to protect slope
49	LGHAZ	Non-existing longitudinal hazard improvement code (column 40)
50	BRGR1	Logic breakdown in placing guardrail between successive bridges
51	BRGR	Bridge approach or departing guardrail lateral offset in wrong location in Box A

A message, "Hazard Improvement Not Cost-Effective," may appear in the data output. This is not an error message, and is not included in the 100-maximum count for automatic program termination. It indicates that the recommended improvement produces, for all intents and purposes, no safety benefit over the hazard currently existing. Under certain circumstances, it indicates that the recommended improvement in fact produces a more hazardous situation than the existing one. The message may be obtained under two circumstances as shown below.

The simplified cost-effectiveness ratio is determined by:

$$\text{Cost-Effectiveness} = \frac{\text{Cost}}{H_B - H_A} \quad . \quad . \quad . \quad . \quad . \quad (\text{Eqn. 4})$$

where

H_A = Hazard index after improvement

H_B = Hazard index before improvement (existing)

If H_A is greater than H_B, the denominator becomes negative. This means that the recommended alternative is more hazardous than the existing situation. Obviously, it is impractical to incur costs to produce a more critical situation than currently exists; therefore, the flag message "Hazard Improvement Not Cost-Effective" is printed out when this occurs and the cost-effectiveness ratio is not computed.

When H_A is only slightly less than H_B, the denominator becomes very small numerically, hence the cost-effectiveness ratio becomes

very large. Based on statistical logic, a lower cut-off level has been incorporated into the model such that when the numerical value of H_B - H_A is less than 0.02, the flag message is printed out and the cost-effectiveness ratio is not computed. The 0.02 level indicates a 55-percent probability of no hazard reduction.

The message, "No Improvements Recommended" merely indicates that for that particular hazard, the recommended safety improvement was "No Improvement Recommended" (code 4, column 40, improvement form). It is not counted as an error message for program termination.

If data errors occur within a grouping, a group cost-effectiveness cannot be determined. Therefore, an error message will be printed out and the message, "End Group" will also appear where the grouping cost-effectiveness value would normally appear. The message "Group" denotes that the cost-effectiveness value represents a total group value.

Analysis Model Data Output

The computer output provides a listing of hazard data, improvement data including costs, and the cost-effectiveness value. Two case examples are presented to illustrate typical output.

Case 1 (point hazard in median). Figure 14 illustrates a typical point hazard--a set of three closely spaced bridge piers in a median. For analysis purposes here, the three individual piers are considered to act as one point hazard with dimensions of the

103
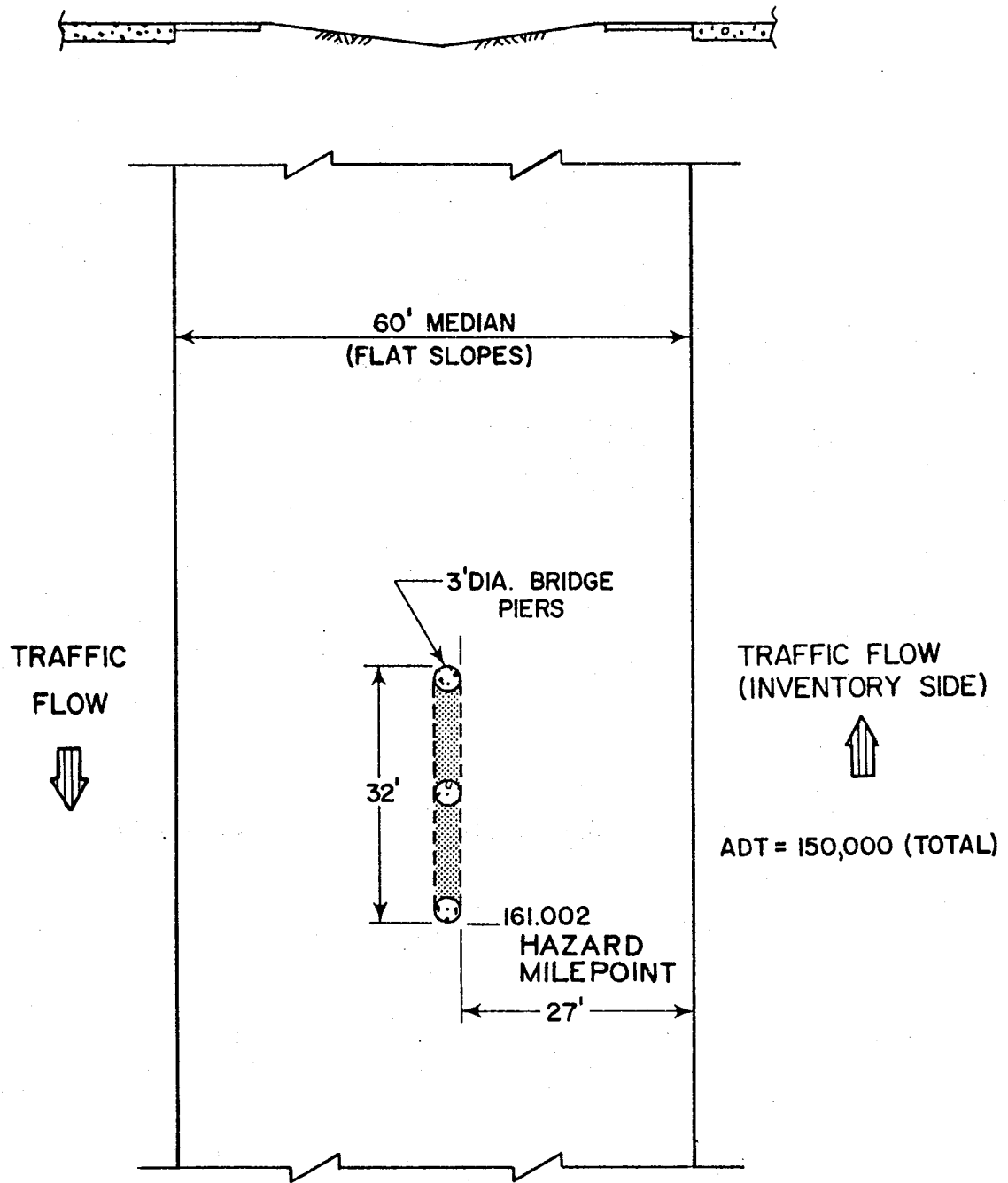
Figure 14. Hazard description and location -- Case 1.

peripheral boundaries because a vehicle cannot pass between two adjacent piers. The four safety alternatives evaluated are (1) remove the piers (replace the bridge with a single span structure), (2) install guardrail around the piers, (3) install a concrete median barrier integral with the piers, or (4) install an impact attenuator system at the end(s) of the pier formation. Figure 15 illustrates the computer program output for each of these four alternatives.

Case 2 (group of hazards in median). Figure 16 illustrates the locations of five hazards in a grouping. Each cluster of trees is considered to be a point hazard within the group. The group also includes a guardrail, a critical slope, and a raised drop inlet. Each hazard within the group is inventoried individually. Although several alternatives exist, only two are discussed here for illustrative purposes. The first alternative includes upgrading the existing guardrail to full safety standards to protect the slope and leaving the other hazards as they currently exist. The second alternative includes guardrail removal, replacing the raised inlet with a flush inlet (removal of hazard) and removal of the two clumps of trees. Figure 17 presents the analysis of these two alternatives.

Interpretation of Analysis Results

The program output basically is of two forms—individual

C O S T   E F F E C T I V E N E S S   P R O G R A M

TYPE HIGHWAY = INTERSTATE (CODE 08)
HIGHWAY CLASSIFICATION = CONTROLLED ACCESS -- INTERSTATE

HIGHWAY NO = 10
COUNTY NO = 230
DISTRICT NO = 19
CONTROL NO = 26
SECTION NO = 12

RECORDING DIRECTION = 1
ADT (1000) = 150
LIFE = 20(YRS)
INTEREST = 8.0(PERCENT)
DATE = 10-74

			H A Z A R D							I M P R O V E M E N T					
HAZARD NO	IDENT CODE	DESC CODE	END TREATMENT BEG END	SEVERITY INDEX	OFFSET CODE	GROUP NO	MILE-POST BEG END		IMPR ALT	IMPR CODE	SEVERITY INDEX	FIRST COST ($)	PRESENT WORTH ($)	ANNUAL COST ($/YR)	COST EFFECTIVE VALUE
100	11	1	0 0	82.5	2	0	161.002	161.008	1	1-1-1-0	0.0	225000	224999	22916	10114
100	11	1	0 0	82.5	2	0	161.002	161.008	2	1-2-0-0	*HAZARD IMPROVEMENT NOT COST-EFFECTIVE*				
100	11	1	0 0	82.5	2	0	161.002	161.008	3	1-3-0-0	2.6	1500	1,990	202	96
100	11	1	0 0	82.5	2	0	161.002	161.008	4	1-4-0-0	1.0	10000	12181	1240	576

Figure 15.   Cost-effectiveness program output--Case 1.
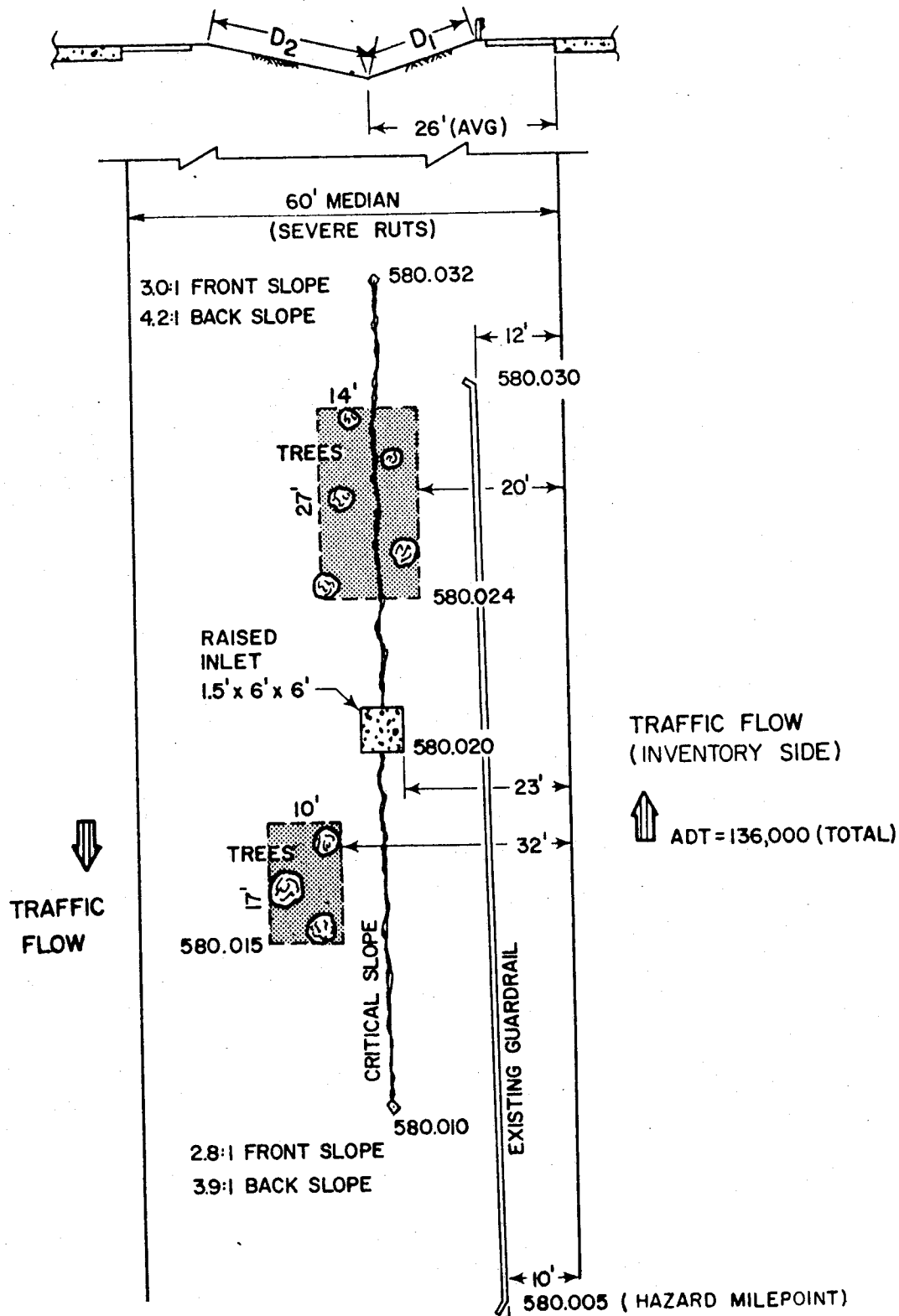
Figure 16. Hazard description and location -- Case 2.

COST EFFECTIVENESS PROGRAM

TYPE HIGHWAY = INTERSTATE (CODE 08)
HIGHWAY CLASSIFICATION = CONTROLLED ACCESS -- INTERSTATE

HIGHWAY NO = 20
COUNTY NO = 163
DISTRICT NO = 15
CONTROL NO = 123
SECTION NO = 2

RECORDING DIRECTION = 1
ADT (1000) = 136
LIFE = 20(YRS)
INTEREST = 8.0(PERCENT)
DATE = 10-74

| | | | H A Z A R D | | | | | | I M P R O V E M E N T | | | | | | |
HAZARD NO	IDENT CODE	DESC CODE	END TREATMENT BEG END	SEVERITY INDEX	OFFSET CODE	GROUP NO	MILE-POST BEG END	IMPR ALT	IMPR CODE	SEVERITY INDEX	FIRST COST ($)	PRESENT WORTH ($)	ANNUAL COST ($/YR)	COST EFFECTIVE VALUE
101	6	2	2 2	17.3	2	333	580.005 580.030	1	2-3-2-0	3.7	650	157	15	GROUP
105	2	0	0 0	50.0	2	333	580.024 580.029	1	4-0-0-0	50.0	0	157	15	GROUP
104	10	1	0 0	82.5	2	333	580.020 580.021	1	4-0-0-0	82.5	0	157	15	GROUP
102	7	2	0 0	60.0	2	333	580.010 580.032	1	3-1-0-0	3.7	1600	2990	304	GROUP
103	2	0	0 0	50.0	2	333	580.015 580.018	1	4-0-0-0	50.0	0	2990	304	121
101	6	2	2 2	17.3	2	333	580.005 580.030	2	2-3-1-0	0.0	500	-1127	-114	GROUP
105	2	0	0 0	50.0	2	333	580.024 580.029	2	1-1-1-0	0.0	250	-1368	-139	GROUP
104	10	1	0 0	82.5	2	333	580.020 580.021	2	1-1-3-0	0.0	2000	631	64	GROUP
102	7	2	0 0	60.0	2	333	580.010 580.032	2	4-0-0-0	60.0	0	631	64	GROUP
103	2	0	0 0	50.0	2	333	580.015 580.018	2	1-1-1-0	0.0	175	315	32	8

Figure 17.   Cost-effectiveness program output--Case 2.

hazards (point hazards, longitudinal hazards or slope hazards) or a group of hazards containing several hazards of the same category or of mixed categories, but to which a single improvement is recommended for all hazards within that group. Case 1 output is typical of the former, Case 2 output illustrates the latter. For improvements to a group of hazards, the message "Group" appears in the cost-effectiveness column adjacent to each individual hazard within the group except the last hazard. The cost-effectiveness value for the complete group safety improvement is shown adjacent to the last hazard in the group.

The output column headings generally are self-explanatory; however, the cost columns require some amplification. The first cost is the net cost to improve the existing hazard to the desired level. Hazard No. 101 in Figure 17 (guardrail) requires a first cost of $650 to upgrade it to full safety standards. The annual cost is the sum of the first cost, the cost of routine maintenance, and the repair cost per collision, all annualized over the life of the object. The present worth is the annual cost discounted to the present at an 8-percent interest rate. Object life and interest rate may be varied in the computer program.

Nature of the Cost-Effectiveness Value

As the cost of an improvement increases, the relative desirability of the improvement decreases; and as the change in hazard increases, the relative desirability of the improvement increases.

Thus, the analysis model as expressed by Eqn. 4, is internally consistent, and the smaller cost-effectiveness value represents the higher priority improvement.

The cost-effectiveness value is expressed as annualized dollars required to eliminate one fatal or serious-injury accident. The numerical cost-effectiveness value at which any given improvement alternative is considered to be cost-effective is arbitrary. However, the cost-effectiveness analysis permits development of a priority listing of alternative improvements, and therefore, improvements having large cost-effectiveness values will be positioned toward the lower end of the priority list.

Priority Rankings for Improvement Alternatives

Cases 1 and 2 represent only a sample of data that would be obtained from a complete inventory. After the improvements throughout a particular section of roadway are evaluated, the various alternatives may be ranked in several ways. They may be ranked by cost-effectiveness value, by individual cost, by cumulative cost with respect to cost-effectiveness value, or in a variety of other ways depending on the desired use.

It is pointed out that a safety improvement program established from the cost-effectiveness analysis must be reviewed carefully to determine the practicality of the improvements. For example, assume that the priority list reflects removal of a system of trees as being the highest priority. With the current emphasis on

110

beautification and preservation of natural beauty, it may not be politically feasible to remove the trees, particularly if these same trees were planted as part of a recent beautification program. Sound engineering is a vital ingredient in evaluating the output and establishing a safety improvement program.

7. FIELD TESTING THE PROCEDURE

It is anticipated that the procedures developed in this research study will undergo statewide implementation by the Texas SDHPT. Since the methodology will become an operational procedure to be responsive to the Federal Highway Administration requirements for a formalized safety improvement evaluation technique, it must satisfy operational requirements imposed by implementation on existing highways.

The validity of the complete application procedure—hazard identification, hazard inventory, hazard improvements, and analysis model—is highly dependent upon the strengths and weaknesses of each of the four facets. The adequacy of each of the data forms is influenced by the completeness of the initial hazard identification list. For example, a hazard encountered in the field but not included in the inventory list could not be inventoried because no provision was made on the inventory form to code it. Similarly, no improvement alternatives could be coded on the improvement form. Problems of this nature can be overcome by the addition of hazard identification or descriptor codes; however, they must be assigned hazard indices and incorporated into the analysis model prior to operation. The hazard inventory and improvement forms represent the nucleus of the analysis model because they are the sole source of input data describing both the suggested improvement and the existing hazard to which safety comparisons are made.

112

Modifications to the forms can heavily influence the computer

analysis program, thus it was imperative that they be fully tested

prior to development of the analysis model.

The procedure was developed in a "building block" fashion with

each "block" undergoing repeated field trials and subsequent modi-

fication as necessary to validate its real world application before

the next was undertaken. The validation techniques are discussed

in this section.

Identification of Roadside Hazards

Selection of the roadside obstacles for the hazard inventory

list was accomplished primarily by trial of a basic list along

several highways in various geographic areas of the state. Since

the list of applicable hazards was vital to development of the

complete procedure, considerable attention was given to assure its

completeness.

The initial list included most of the primary classifications

(identification codes) shown previously in Table 1. Field trials

were conducted on rural and urban highways using the basic list to

determine if each roadside obstacle encountered could be classified

within one of the primary categories. It was apparent during the

first few field trials that the basic list needed additional cate-

gories. These were added and the process was repeated until the

basic list was comprehensive enough to allow classification of any

roadside obstacle found on the highways selected.

A secondary requirement to identifying roadside hazards was the assignment of severity indices to each. The impact severity of a barrier curb is different from that of a mountable curb, yet both fit the basic categories of "curbs". Similarly, several types of guardrail installations can be found. Relatively new installations with 6 ft.-3 in. post spacing exhibit different impact severity than do, for example, older installations with 12-ft. post spacing. To differentiate between different configurations of the same basic obstacle, it was necessary to subdivide many of the primary categories. Thus, the descriptor codes in Table 1 were developed. The sub-categories, like the primary categories, were established by repeated field trial on Texas highways.

Highways selected for field trials included divided and undivided facilities in and around Austin, Houston, Ft. Worth, and Bryan, Texas.

Hazard Inventory and Improvement Forms

More than two dozen major modifications to the initial inventory and improvement forms resulted from an equal number of field trials. In approximately half these cases, the modification consisted essentially of a completely new format for each form, particularly in the early stages of development.

The field tests were conducted on both forms simultaneously by inventorying hazards and attempting to code feasible improvements

for each. When a hazard could be inventoried but a desired improvement could not be coded, the improvement form was expanded to accommodate this particular alternative. Similarly, the inventory form was modified to allow coding of each hazard. Since the two data forms must be compatible, a change in one form often necessitated changes to the other.

The primary objective in field trial of the forms was to develop a data input set that was as comprehensive as possible to meet operational requirements. A second, but highly important, requisite of validation tests was to design a set of forms that would provide the needed information, yet be completed quickly. The achievement of this requirement involved continued format redesign and changing of the column coding messages for clarity of intended meaning. Repeated field trials produced several interesting phenomena which played an important part in the form structure. For example, a pattern was noticed in the sequence in which the safety team described each hazard. They first identified the object by name, then the side of the roadway on which it was located. The third determination was that it was either a single hazard or a group of several hazards. The location (milepoint) was not recorded until the vehicle arrived at the obstacle. Other such trends were noticed and, where possible, the form was structured to allow the inventory personnel to record these data in the same sequence from left-to-right across the form.

The field test studies led to the classification of hazards

within the three primary categories--point hazard, longitudinal hazard, and slopes. This was done to reduce the search time on the form for data entry. The same categorization was used in the improvement form design to maintain compatibility and take advantage of a certain degree of programmed learning.

Experienced key-punch operators were consulted during the development of the two forms to seek their advice on ways that the forms could be better designed to suit their needs. It was found that key-punch time and errors could be substantially reduced when the forms were designed such that all entry locations were arranged in rows across the page because the key-punch operators were accustomed to this format. Also, since the forms were designed to require that only one of the three primary categories be completed, the key-punch time could be reduced further if only those rows containing data were quickly identifiable. Space was provided on the form where the inventory recorder could insert a check mark adjacent to any row containing data. The key-punch operators could quickly recognize and key-punch the particular rows of data, and ignore those rows not containing a check mark.

The key-punch operators suggested that all consecutively completed spaces be assigned sequential computer card column numbers (no spaces between entries) because rows of data containing spaces to be left blank produce a much higher probability of key-punch errors. Therefore, all data entry locations were numbered sequentially on both forms with no spaces between columns.

Analysis Model

Having field tested the developmental stages with real world application greatly enhanced the confidence that could be placed on the analysis model. In essence, the reliability of the model was influenced by the reliability of the components which formed the input informational needs.

Validation of the model can be considered in two separate but interlinked phases--validation of the computer model, mechanical operation and validation from the standpoint of accomplishing the primary objective by providing the capability to evaluate all desired improvement alternatives.

Computer Program Validation

The program validation (de-bug operations) was given first priority because, in order to evaluate the capabilities, the model had to be mechanically operative. The complexity of the model dictated stage development with validation of each stage in sequence. For this reason, the model was assembled in small-package subroutines. Each subroutine was debugged individually using test case data designed to force execution of the particular subroutine. As each subroutine was validated for mechanical operation, it was linked with others until the total model was developed. Test case data were then developed to test the operation of the total computer model before attempts were made to analyze field data.

All computer program validation studies were conducted on the

computer facilities at Texas A&M University. The operational model is stored on Texas SDHPT computer equipment in Austin and accessed from remote terminals located throughout the state. Although both computer facilities operate IBM 360 equipment, it was necessary to determine if system inconsistencies existed between the two. Therefore, the model was placed on line in the SDHPT computer and tested with the same test case data input used during debug operations at Texas A&M University. Minor adjustments were made to adapt the model to the SDHPT equipment. The remote terminal access operations were then tested by inputing test case data at remote terminals in Austin, Houston, and Ft. Worth.

Full-Scale Field Implementation

One SDHPT District was selected to validate the procedure and the analysis model under operational conditions. The Ft. Worth District (District 2) inventoried and analyzed in excess of five thousand roadside hazards during approximately six months. Separate data files were maintained for problem situations. At the completion of the data collection, the problem areas were categorized into one of the four primary aspects of the procedure. The hazard identification list was expanded where necessary to permit coding obstacles not previously included. The hazard inventory form was modified to accommodate the coding of hazards that could not be conveniently inventoried before. The improvement form

118

was expanded to include unique alternatives that had not been iden-
tified during initial field trials.

The entire analysis model was reworked and expanded to be
responsive to the problems encountered in the full-scale implemen-
tation testing. All data collected were re-analyzed after the
major program revision until the problem situations were alleviated.
The procedure reported in this document represents the current
status of the identification list, the inventory and improvements,
and the analysis model as a result of all validation studies. Since
the latest procedural modifications were incorporated, the complete
controlled access roadway mileage and considerable non-controlled
access roadway mileage in approximately eight of the twenty-six
Districts has been inventoried and analyzed with only very minor
problems arising during procedure application.

Training courses have been administered to each of the twenty-
six SDHPT Districts to familiarize the safety personnel with the
procedures, capabilities and usefulness of the safety improvement
program. The training courses included both theory and actual on-
site operational trials of the procedure including remote-terminal
computer access and discussion of results obtained.

The conduct of the safety improvement analysis program is
administered through File D-18S of the State Department of Highways
and Public Transportation.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

The results of the research outlined in this report provide a
rational procedure by which safety alternatives for roadside hazards
may be evaluated and priorities may be established to develop a
safety improvement program. This procedure utilizes a safety evalu-
ation team to conduct a comprehensive roadside inventory and recom-
mend viable safety alternatives. The evaluative process and data
forms developed herein provide an implementable method of obtaining
the informational needs necessary to employ cost-effectiveness tech-
niques in a consistent manner. The procedure can be applied through-
out large regions, yet reflect cost differences that may exist with-
in or between particular regions.

The achievements of this research have extended current tech-
nology from a basic concept for evaluating freeways to a practical
application procedure that is readily implementable on both con-
trolled access roadways both urban and rural, and non-controlled
access rural roadways using computerized techniques. In addition,
the concept and procedures developed in this research may be applied
at the design stage to evaluate alternative designs; they are not
limited to evaluation of existing hazards.

The process developed in this research provides a technique to
put a basic concept to work in the area of roadside safety for all
types of roadways—a technique that is readily adaptable to individ-
ual user requirements and agency policies. Full success of the

process as an administrative tool for the development of a priority safety improvement program is dependent upon its flexibility for modification and expansion that may result from further field implementation and from subsequent research. The process has this flexibility. Only through actual use can the flexibility be exercised.

Recommendations

Although the procedure developed herein can be implemented immediately, subsequent research should contribute to refinement and growth of the process. Specific recommendations for future research are listed as follows:

1. Vehicle encroachment characteristics for non-controlled access, particularly non-median divided highways, should be determined. The current analysis model incorporates encroachment data based on research findings concerning median encroachments.

2. Encroachment data applicable for horizontal curvature and bridges should be determined. These geometric features would be expected to influence the encroachment characteristics and, hence, modify the encroachment data for tangent sections on which the analysis currently is based.

3. Continued implementation of the procedure on non-controlled access highways is recommended to identify deficiencies

that may exist in inventorying or improvement alternatives. After sufficient trial time, it is recommended that the process be revised, as appropriate, reflecting the input from the results of the field implementation. It is highly probable that the hazard inventory list will require extension to accommodate additional roadside obstacles that are found alongside the highway.

4. Computerized file systems should be developed to summarize the analysis model output for administrative use in developing a safety priority program. Such file systems must be structured to meet the needs of a particular user.

5. As experience is gained through evaluation of analysis data from inventoried roadway mileage, it may become apparent that certain roadside obstacles currently being evaluated do not exhibit cost-effective improvements. It is recommended that a critical review be made of analysis output to identify those obstacles and directives be given to omit them from subsequent inventorying or to omit certain improvement recommendations that consistently produce non-cost-effective alternatives.

6. Close liaison between design personnel and the safety evaluation team is encouraged. Only through cooperative effort can the results of the roadside safety evaluation be applied at the design stage where they can be most effectively applied to produce safer roadways.

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