DEVELOPMENT OF CRASH RECONSTRUCTION PROCEDURES FOR ROADSIDE SAFETY APPURTENANCES

by

Brian A. Coon

A DISSERTATION

Presented to the Faculty of
The Graduate College at the University of Nebraska
In Partial Fulfillment of the Requirements
For the Degree of Doctor of Philosophy

Major: Interdepartmental Area of Engineering

Under the Supervision of Professor John D. Reid

Lincoln, Nebraska

August 2003

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DISSERTATION TITLE

DEVELOPMENT OF ACCIDENT RECONSTRUCTION

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SUPERVISORY COMMITTEE:

Approved	Date
Signature	8/5/03
Dr. John D. Reid Typed Name	
Signature	8/5/03
Dr. M. Susan Hallbeck Typed Name	
Signature	8/5/03
Dr. John R. Rohde Typed Name	
Signature	8/5/03
Dr. Dean L. Sicking Typed Name	
Signature	
Typed Name	

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DEVELOPMENT OF CRASH RECONSTRUCTION

PROCEDURES FOR ROADSIDE SAFETY APPURTENANCES

Brian A. Coon, Ph.D.

University of Nebraska, 2003

Advisor: John D. Reid

Roadside safety appurtenances, including flexible longitudinal barriers, end terminals, and crash cushions, are designed to protect errant vehicles from roadside hazards. However, in order to design, test, and determine appropriate warrants, the real-world ran-off-road impact conditions must be identified. Most importantly, this includes the distribution of the angles and speeds at which vehicles exit the roadway. This requires the reconstruction of ran-off-road crashes.

However, reconstruction procedures for longitudinal barriers, crash cushions, and many other roadside hazards are not available in literature. This dissertation details the development of reconstruction procedures for ran-off-road crashes and illustrates its implementation through the development of procedures for flexible longitudinal barriers, end terminals, and crash cushions.

These procedures will be used in NCHRP Project 17-22, entitled "Identification of Vehicular Impact Conditions Associated with Serious Ran-Off-Road Crashes" in order to determine the angles and speeds during an off-road excursion. This information will then be used for refining the guidelines for roadside safety countermeasures and for calibrating roadside safety simulation models, as well as identifying the roadside features involved in the greatest number of serious crashes. This will help designers spend safety dollars on improvements that will have the greatest likelihood of reducing serious injuries and fatalities.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. John Reid, for the opportunity to attend graduate school and his ever-present help and moral support. His patience and moral clarity cannot be overstated and are always greatly appreciated.

Dr. Dean Sicking, the Director of the Midwest Roadside Safety Facility, has both my heartfelt appreciation for his assistance in my research and my respect as an engineer and as an individual. Dr. Sicking has funded my entire graduate education, through the Midwest States' Pooled Fund for my Master's program and through National Cooperative Highway Research Project 17-22 for my Doctorate. Without his assistance and funding, my graduate education would not have been possible.

Dr. John Rohde, my Master's advisor and doctoral committee member, has my sincere appreciation for the help he has given me over the years. The space is too short to write all that should be said – thank you for everything.

I greatly appreciate Drs. Susan Hallbeck and Shane Farritor for serving on my Doctoral committee. It has been a journey and your help has been greatly appreciated.

Thanks go to Dr. Ron Faller for the help he has provided throughout my graduate career. He and staff of the Midwest Roadside Safety Facility have my appreciation for all their help. Many thanks to Karla Polivka for reading what could only remotely be referred to as "English" and to Bob Bielenberg for his expertise in LS-DYNA.

Finally, I want to thank my family for all their support. Specifically, I want to thank my son, Alec Coon, for his patience and understanding while I completed my studies. He is the most wonderful thing ever to be brought into my life.

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1 INTRODUCTION

When a vehicle exits the traveled way and encroaches on the roadside, the best chance for reducing crash severity is to offer roadsides free of fixed objects and other hazards [1]. However, logistics and economy frequently prohibit the removal of all roadside hazards. Design alternatives, in order of preference, include:

1. Remove the obstacle.
2. Relocate the obstacle.
3. Make the object breakaway or safely traversable.
4. Shield the object with a longitudinal barrier or crash cushion.
5. As a last alternative, delineate the obstacle.

The determination of the benefit-to-cost ratio for each alternative requires an accurate understanding of the real-world conditions where ran-off-road crashes occur. Most importantly, this includes the distribution of the angles and speeds at which vehicles exit the roadway. This information can then be used for refining the guidelines for roadside safety countermeasures and for calibrating roadside safety simulation models, such as the Roadside Safety Analysis Program (RSAP), as well as identifying the roadside features involved in the greatest number of serious crashes.

1.1 Purpose of Research

This research was developed for National Cooperative Highway Research Program (NCHRP) Project 17-22, entitled "Identification of Vehicular Impact Conditions Associated with Serious Ran-Off-Road Crashes." The primary goal of NCHRP Project 17-22 is to identify the vehicle types, impact conditions, and site characteristics

associated with serious injury and fatal crashes involving roadside features and safety devices.

NCHRP Project 17-22 is a retrospective examination of ran-off-road crashes by performing crash reconstruction of such crashes from the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) by the National Highway Traffic Safety Administration (NHTSA). The distribution of the impact speeds, angles, and orientations will be used to create a database that can then be used to identify a practical worst-case testing regimen.

Real-world data on ran-off-road crashes will help designers spend safety dollars on improvements that will have the greatest likelihood of reducing serious injuries and fatalities. These improvements will also serve to foster the spectrum of commonly available roadside design alternatives for appropriate field conditions.

1.2 Crash Reconstruction

Analysis of ran-off-road crashes requires the application of accurate crash reconstruction methodologies. Crash reconstruction involves using engineering principles, such as conservation of energy and conservation of momentum, to determine how a crash occurred and to estimate the initial speed and position of the vehicle.

Crash reconstruction primarily entails calculating energy losses and gains after the vehicle leaves the roadway. This requires qualitative and quantitative information about the crash; while the logistical specifics of a particular crash may be unique, ran-off-road crashes generally involve specific groups of objects, such as trees, embankments, or

guardrails. The fixed-object impact frequency for fatal crashes by object struck from the Fatality Analysis Reporting System (FARS) data for 2000 is shown in Table 1 [2].

Table 1. Object Struck as First Harmful Event From 1999 FARS Data.

Object	Frequency
Tree	2,997
Embankment	1,213
Guardrail	1,078
Utility Pole	1,018
Ditch	887
Curb	681
Culvert	592
Fence	490
Sign Support	368
Other Post/Support	308
Concrete Barrier	275
Bridge Rail	158
Bridge Pier/Abutment	155
Wall	119
Luminaire Support	103
Boulder	79
Building	79
Shrubbery	56
Bridge Parapet	36
Equipment	26
Fire Hydrant	25
Other Longitudinal Barrier	23
Snow Bank	23
Traffic Signal Support	22
Unknown	22
Impact Attenuator	11
Other Fixed Object	506
Other Object (not fixed)	135
Total	***11,485***

1.3 Absent Reconstruction Procedures

Many ran-off-road crashes, such as those with rigid walls or poles, can be reconstructed using well-established reconstruction procedures [3]. However, impacts with longitudinal barriers, crash cushions, and many other roadside hazards do not have reconstruction procedures available in literature. Because of the prevalence of crashes involving roadside hazards lacking available reconstruction procedures, the development of appropriate reconstruction procedures for these devices is required.

1.4 Research Approach

The development of new reconstruction procedures involves a comprehensive examination of the existing procedures, an examination of full-scale and component testing performed, and the availability and applicability of computer simulation software. This generalized approach will allow for new procedures to be developed and for future additions to the database with vehicle fleet changes, future speed limits changes, and other changes that may affect the nature of ran-off-road crashes.

This dissertation is divided into ten chapters. This first chapter serves as an introduction and overview of the work. Chapter 2 examines the prior work in the field of crash reconstruction. Both a perspective of ran-off-road crashes and crash reconstruction are discussed.

Chapter 3 discusses the nature of reconstruction procedures and a general methodology for developing reconstruction procedures. This includes examining reconstruction procedures in literature and the availability and analysis of crash test results.

The information available to reconstruct a crash is delineated in Chapter 4. Sources of data include scale diagrams, photographic evidence, and police reports. Chapter 4 also suggests other resources for obtaining data, such as the National Automobile Dealer's Association (NADA) and the American Automobile Manufacturer's Association (AAMA).

Due to the hundreds of roadside devices and obstacles, with some designs of devices barely distinguishable from others, Chapter 5 examines device identification. Correct identification of a roadside device is critical to accurate reconstructions. This includes the identification of longitudinal barriers, guardrail end terminals, crash cushions, concrete barriers, *et cetera.*

Chapter 6 details procedures required to develop reconstruction procedures. The use of basic engineering principles, full-scale crash test data, component testing, as well as the use of computer software is discussed.

Examples of three reconstruction procedures are detailed in Chapter 7. These procedures, listed in detail in the Appendix, were developed for longitudinal barriers, energy-absorbing guardrail end terminals, and inertial barriers (sand barrels).

Chapter 8 lists the conclusions of the research effort of developing reconstruction procedures to aid in the identification of the real-world conditions where ran-off-road crashes occur. This information will allow better test procedures for determining the suitability of an appurtenance for use on the National Highway System (NHS). Ultimately, this will lead to a safer roadside environment, which will save lives and reduce injuries during ran-off-road crashes.

Opportunities for future work are discussed in Chapter 9. This includes the development of reconstruction procedures for additional roadside devices and the examination of the effects of impact orientation.

DRAFT: Thursday, July 24th 2003

2 PRIOR WORK

Identification of the real-world conditions where ran-off-road crashes occur requires that the encroachment rates and conditions (impact angle, speed, and vehicle orientation) be identified. An examination of prior studies reconstructing significant numbers of ran-off-road accidents is helpful to identify procedures that have proved successful previously and to identify potential pitfalls to be avoided.

Research determining vehicle encroachment rates have focused on two areas: (1) the use of vehicle tracks along the roadside to estimate encroachment angles and lengths and (2) the use of accident records and crash reconstruction.

2.1 Hutchinson and Kennedy Study

Hutchinson and Kennedy (H&K) performed the landmark study of vehicle encroachments in medians through the examination of vehicle tracks in 1966 [4]. This consisted of planned, weekly coverage of entire lengths of selected highway segments to locate and evaluate evidence of vehicle encroachments. Much of the data from the H&K study was collected during winter months on snow-covered medians of rural divided highways with speed limits of 112.7 km/h (70 mph).

Surveillance was performed by two-man teams who patrolled the highway in specially marked, slow-moving vehicles. A visual record of each encroachment consisted of a sketch of the path of the vehicular movement with dimensions, highway cross-section dimensions, type of median cover, approximate time of occurrence, and other pertinent data. A visual record of each encroachment was compiled with a series of colored and black and white pictures.

The encroachment data from the H&K study is the basis of the runout lengths in the Roadside Design Guide. Additionally, the data was also used for the development of the computer simulation program ROADSIDE.

2.2 Cooper Study

Cooper performed an extensive study in Canada through the use of vehicle tracks in 1978 [5]. Cooper collected encroachment data during the summer/autumn months of June through October along the roadsides of both divided and undivided highways. Most of the highways had 80.5 - 96.6 km/h (50 - 60 mph) speed limits.

Cooper found markedly lower encroachment lengths than H&K. Much debate has been given to whether the encroachment lengths from the H&K and Cooper studies are similar. It has been shown that once both studies are corrected to match encroachment angle distributions from real-world data, there appears to be good agreement between the two studies [6].

2.3 Probability Models

Mak developed an encroachment model under NCHRP Project 22-9, "Improved Procedures for Cost-Effectiveness Analysis of Roadside Features." Project 22-9 was the basis for the Roadside Safety Analysis Program (RSAP) [7]. Mak determined a base or average encroachment frequency based on highway type and traffic volume and then modifying the base frequency to account for specific highway characteristics such as vertical and horizontal alignment, number of lanes, and annual traffic growth factor.

RSAP determines the probability of an accident given an encroachment using the Monte Carlo simulation technique where a large number of encroachments are simulated

and those causing crashes are identified. Given information on the roadway design and the location of roadside obstacles, the encroachment models will use a series of conditional probabilities to estimate the ran-off-road crash costs associated with a given design. The designer can use this information to evaluate alternative designs.

2.4 Crash Reconstruction

The field of crash reconstruction is an extremely mature field [8]. Vehicle kinematics and kinetics, the reconstruction of rear-end collisions, and even the determination of whether or not brakes had been applied by the analysis of light bulb filaments are well-documented and mature areas of engineering [3]. Research on the development of generalized reconstruction procedures for categories of roadside objects is of particular interest to this research.

2.4.1 Rigid Barrier Impact Reconstruction Procedure

Mak, Sicking and Lock developed procedures for reconstructing rigid barrier impacts [9]. The procedure is based on the principle of conservation of energy, utilizing empirical relationships derived from full-scale crash test results. Computer simulation of the impacts is performed using a new subroutine developed for the software package CRASH3 [10].

The new subroutine, CMB, implements an iterative scheme to produce an initial estimate of the energy lost during the rigid barrier impact. CMB uses vehicle crush energy and the length of barrier contact to produce an initial estimate of the energy lost during the rigid barrier impact. This energy loss is then added to the CRASH3 trajectory analysis to produce an initial estimate of the original impact speed. If the vehicle crush

energy then matches the energy associated with the lateral velocity of the impacting vehicle, the result is believed to be reasonably accurate. If not, the vehicle crush energy is adjusted appropriately and a new estimate of the impact speed is generated. This iterative procedure has been found to give reasonably good estimates of impact speed when compared with full-scale crash tests.

Also examined in this study were cases where vehicle rollover occurred. The computer software program HVOSM was used to determine energy losses from roll distances. These curves, known as Kildare Curves, are shown in Figure 1 [9]. It was found that roll distance is relatively unrelated to the tripping mechanism. That is to say, roll distances are not greatly affected whether high tire side forces are applied instantaneously or whether they are applied slowly.

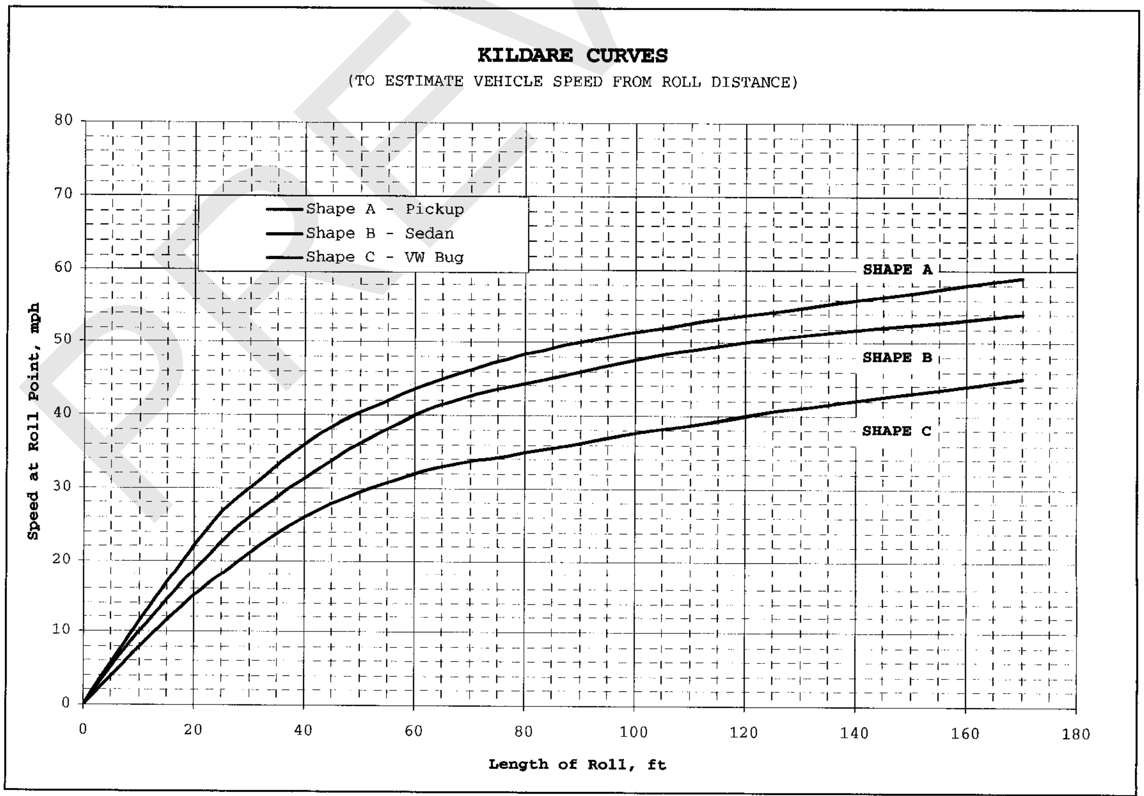

Figure 1. Curves developed using HVOSM to simulate vehicle rollover accidents [9].

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2.4.2 Longitudinal Barrier Special Studies

The Longitudinal Barrier Special Studies (LBSS) file was developed to augment the National Accident Sampling System (NASS), which is a probability sample of all police-reported crashes occurring in the U.S. from year to year [11]. The LBSS file, which was revised to meet changing analytical requirements, was cleaned and recoded to ensure consistent coding of data from year to year. This was found to be essential in developing a usable, clean database.

Scientex researchers examined several reconstruction procedures to determine the most appropriate method(s). Features of the procedures taken into consideration included the time and effort required to develop or modify the procedure, any previous use of the procedure, and an evaluation of the previous efforts.

For barrier Length-Of-Need (LON) speed reconstructions, the basic principle of conservation of energy was used. The total energy absorbed in a crash comes from the following three components:

$$E_{\text{total}} = E_{\text{vehicle crush}} + E_{\text{barrier deformation}} + E_{\text{vehicle trajectory}} \quad [1]$$

The energy due to vehicle crush was found using the visual method and equations from Campbell [12]. The extent of the crush was determined visually by inspecting crash vehicles.

Barrier deformation energy was obtained from curves of impact severity index versus maximum dynamic deflection (number of failed posts was used for cable systems) developed for flexible longitudinal barriers. This is the same impact severity index that

was used in NCHRP Report 230 and is currently still implemented in NCHRP Report 350 and is equal to:

$$IS = \frac{1}{2} mV^2 \sin^2 \theta \qquad [2]$$

Where:

IS = Impact Severity (Severity Index)
m = Mass of impacting vehicle
V = Velocity of impacting vehicle
θ = Impact Angle

These curves were based on a series of computer simulations performed using BARRIER VII as part of work performed by Calcote [13]. In order to adjust for differences between the permanent and dynamic deflections, a scaling factor was used. This scaling factor was created by dividing the dynamic deflection by the permanent deflection of several full-scale crash tests on standard guardrails.

Vehicle trajectory was based on the energy absorbed using equations of motion. Adjustments were made for skidding and sliding. For rotating vehicles, the distance traveled was based on the angle of rotation and the radius. The energy absorbed by the rotation was also calculated.

2.4.3 NCHRP Project 17-11

Research to improve the trajectory data used in the encroachment model is included in NCHRP Project 17-11 "Recovery-Area Distance Relationships for Highway Roadsides" [14]. This effort developed relationships between recovery-area distance, sideslopes and other factors for various highway functional classes and design speeds. This project also involved the creation of a crash database.

2.4.4 Reconstruction Procedure for Pole Accidents - Labra and Mak

An examination of existing simulation and analytical models was performed for pole crashes by Labra and Mak [15]. Software programs designed for reconstructing pole accidents, including DASF, LUMINAIRE, MODASF, and UTILITY POLE were deemed unusable due to the significant amounts of information required to reconstruct the accident, including the structural properties of individual poles and the physical properties of a luminaire transformer base. Therefore, a procedure to create a new subroutine for the well-validated CRASH was developed.

Examined analytical models made assumptions and simplifications in order to keep the mathematics and calculations at a manageable level. The key assumption was that the post failed in a shear mode and that shearing is instantaneous once the shear strength or base fracture energy is reached. While this assumption is valid for metal bases, timber poles cannot adequately be modeled, since wooden posts fail mostly in a bending mode with fiber striping.

Pole impacts were divided into three categories: (1) no noticeable pole damage, (2) partial fracture of the pole, and (3) complete separation of the post. In cases where there was no noticeable pole damage, the pole was treated as a rigid object. It was assumed that the pole did not absorb energy and that all energy dissipation that occurred was due to vehicle crush. Equations for the fracture of wooden utility poles are shown in Table 1 and graphically represented in Figure 2.

Table 2. Equations Used to Derive Figure 2.

Pole Circumference (in.)	Extent of Fracture	Breakaway Fracture Energy (ft-lb)	Curve Segment
≤ 26	None	0	1
	Partial	$\frac{1}{2}(20{,}000 - (1.4 \times 10^{-5})\, C^{4.38})$	3
	Complete	20,000	4
>26	None	0	5
	Partial	$\frac{1}{2}((1.4 \times 10^{-5})\, C^{4.38} - 20{,}000)$	3
	Complete	$(1.4 \times 10^{-5})\, C^{4.38}$	2

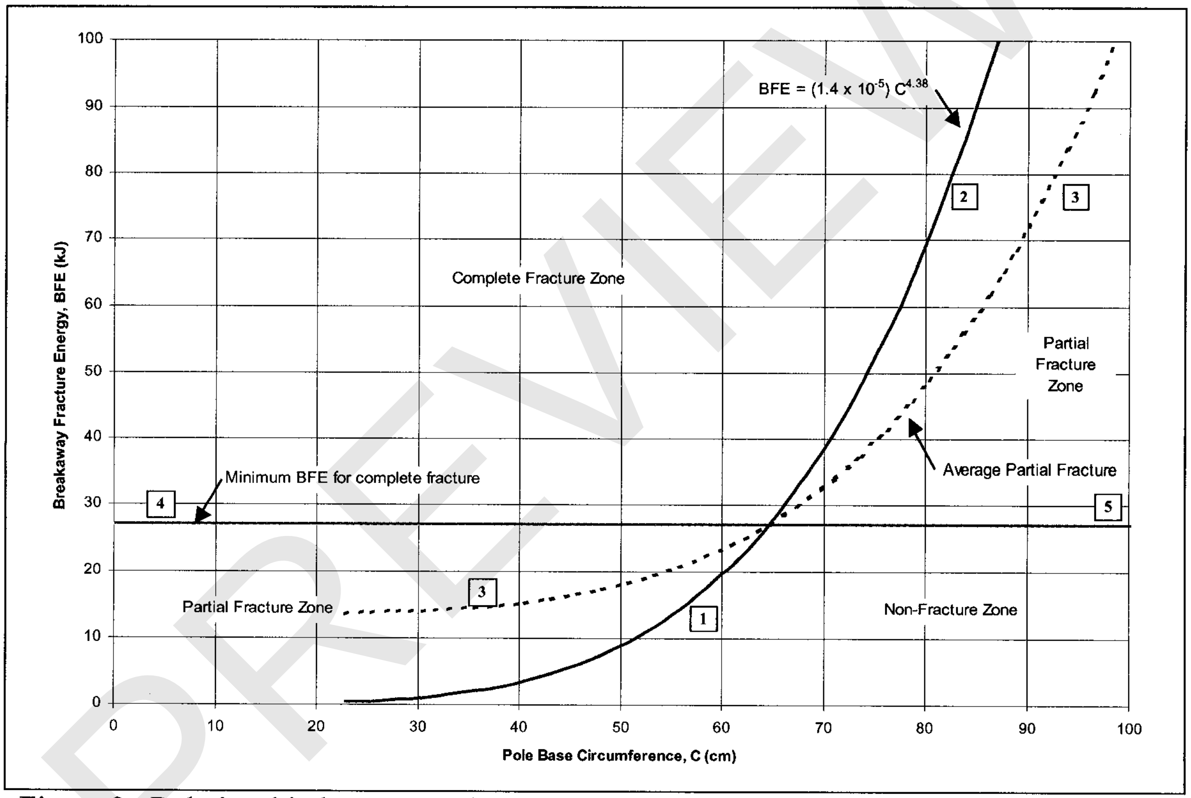

Figure 2. Relationship between Pole Diameter and Fracture Energy.

The study determined that the minimum elements required for a complete reconstruction of a pole impact are: (1) material and type of pole or base, (2) length of pole, (3) cross-sectional dimensions at base of pole, (4) type of base / anchoring mechanism, (5) type of breakaway design, and (6) damage extent of the pole. It was

found to be desirable to have the following information: (1) height of break / length of broken segment, (2) cross-sectional dimensions at the top and bottom of the broken segment, (3) final resting position of the pole, and (4) manufacturer of the breakaway device.

The analytical procedure for the five full-scale impacts varied between -5.5% and 45.9% of the actual energies. However, the procedure was never coded into subroutines for CRASH and its numerical intensity far exceeds its level of accuracy if performed manually. While the procedure was never coded into subroutines for CRASH, this methodology provides a usable way to reconstruct pole impacts.

2.4.5 Reconstruction Procedure for Pole Accidents - Kent and Strother

This study performed a literature review, a series of one-eighth scale-model pole/pendulum impacts, and an analytical study using static analysis and dynamic finite element modeling of vehicle/pole impacts [16]. A methodology was developed correlating the scale-model testing of several species of wood to full-scale impacts. It was assumed that the pole or tree in question acts as a cantilevered beam when impacted with no significant base translation and/or rotation in addition to a fracture.

The implementation of this methodology requires the following additional data be known during the reconstruction:

1. The geometry of the struck pole/tree (diameter and height).
2. Species of wood making up the pole or tree in question (however, the accident reconstructionist can assume the pole or tree was constructed of a material that will absorb a minimum amount of energy).

3. The moisture content of the pole or tree in question (poles can generally be assumed to be of low moisture content (i.e. less than six percent), trees generally have moisture contents greater than 20 percent).
4. The nature of damage to the pole or tree, including the completeness and height of the fracture.

A graphical summary of the methodology for reconstructing pole impacts is shown in Figure 3. Wood species and moisture content may be necessary to accurately reconstruct wood pole impacts. However, the acquisition of this data would require expertise generally beyond that of the average technician unless properly educated.

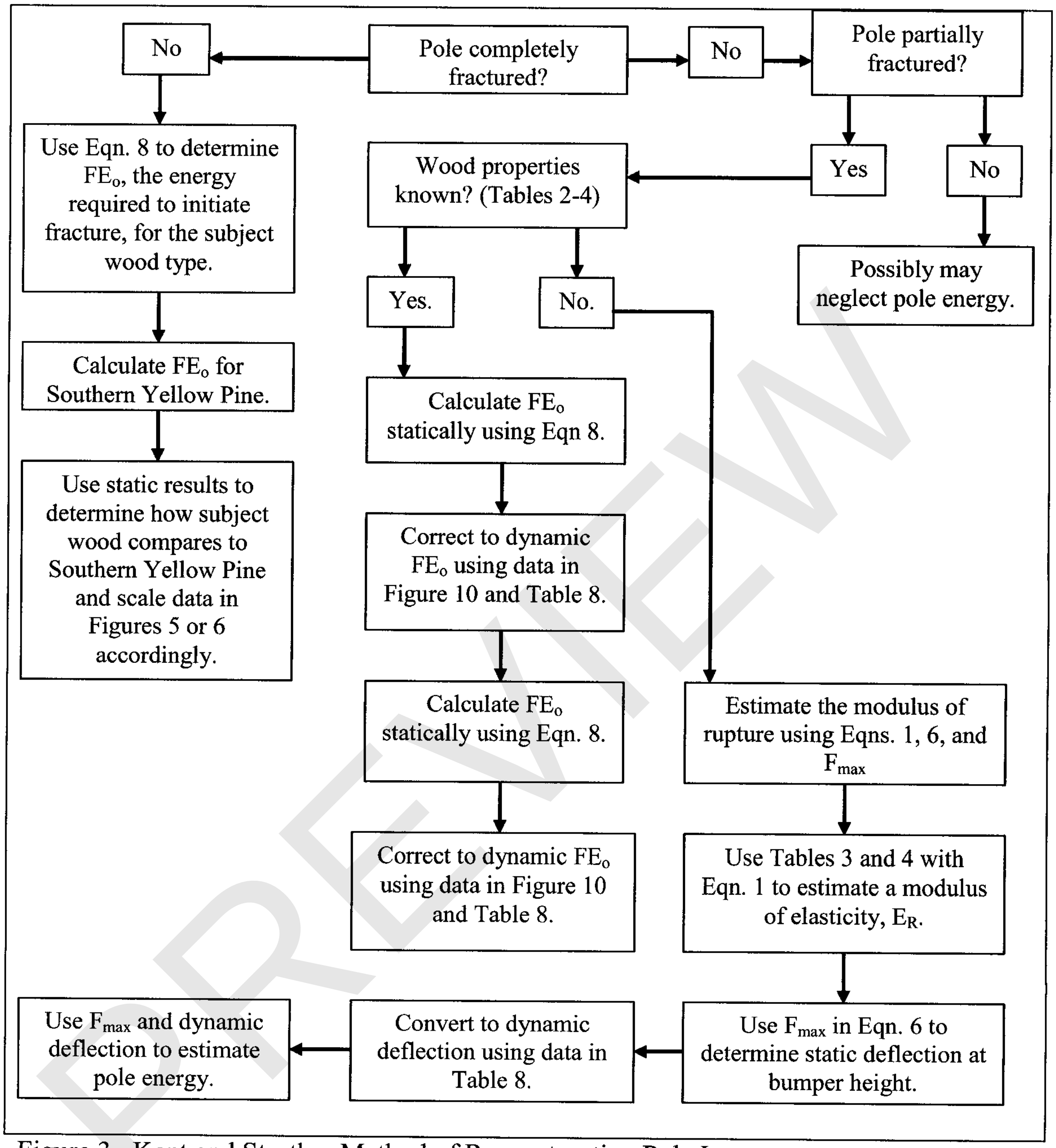

Figure 3. Kent and Strother Method of Reconstructing Pole Impacts.
(Equations listed are found in Reference 16)