FEASIBILITY STUDY OF BREAKAWAY STUB CONCEPT FOR WOODEN UTILITY POLES

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in cooperation with
LINCOLN ELECTRIC SYSTEM
and
LINCOLN TELEPHONE AND TELEGRAPH COMPANY

CIVIL ENGINEERING DEPARTMENT
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UNIVERSITY OF NEBRASKA

Engineering Research Center
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ABSTRACT

Key Words: roadside safety, wooden utility pole, computer simulation, full-scale vehicle crash test, cost-effectiveness

In the development of roadside safety improvement programs, many types of obstacles have been identified as being hazardous. In some cases these obstacles can be removed or relocated. The utility pole is an example of an obstacle that cannot be relocated easily. The severity of vehicle impacts with roadside obstacles can be reduced by making modifications to the obstacle in place. This study investigates the feasibility of a breakaway utility pole concept developed by the Transportation Research Program at the University of Nebraska-Lincoln.

Pendulum and full-scale vehicle crash tests were conducted to determine the feasibility of the breakaway concept as well as to provide an understanding of the mechanics involved. A computer simulation model was developed and validated with data obtained from the tests in order to assist in the evaluation of the breakaway concept. A cost-effectiveness analysis was performed using severity index and probability of injury values calculated from results of full-scale tests and the computer simulations.

Three full-scale vehicle crash tests were conducted using 40 ft. Class 4 Southern Pine utility poles. A large test vehicle (4450 lbs) was used for the first test and a small vehicle (2250 lbs) was used for the final two tests. The results of this study indicate that:

(1) the breakaway concept is effective in reducing impact severities and therefore the probability of injury

(2) the breakaway concept is cost-effective.

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Department of Civil Engineering

Donald M. Edwards, Director
Engineering Research Center

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The 40 ft. class 4 utility poles and hardware for the full-scale crash tests were supplied and installed by the Lincoln Electric System.

The 25 ft. utility poles for the pendulum tests were supplied by the Lincoln Telephone and Telegraph Company.

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INTRODUCTION

During the past several years considerable attention has been given to improving roadside safety by removing obstacles from the immediate vicinity of the traveled way. In many cases where these obstacles could not be removed, or relocated, they have been modified so they would break away when struck by a vehicle. Research and accident experience have shown that breakaway sign supports and luminaire supports are effective in reducing the severity of vehicle impacts. However, not until recently has much attention been given to utility poles, which represent one of the most serious roadside hazards, particularly in urban areas, because of the relatively high frequency with which they are struck and the relatively high severity of these impacts. Figure 1 shows a number of typical utility pole installations in the Lincoln area.

In February 1978, a concept for a breakaway utility pole was proposed by the Transportation Research Program at the University of Nebraska-Lincoln (UNL). During the next year, meetings were held with representatives of the Lincoln Electric System and Lincoln Telephone and Telegraph Company as well as the Nebraska Department of Roads, City of Lincoln, and Federal Highway Administration. The purpose of these meetings was to discuss the proposed concept and to solicit the involvement of these organizations in a study of its feasibility. Based on the interest expressed at these meetings the Department of Civil Engineering and the Engineering Research Center at the UNL provided funding for such a study.

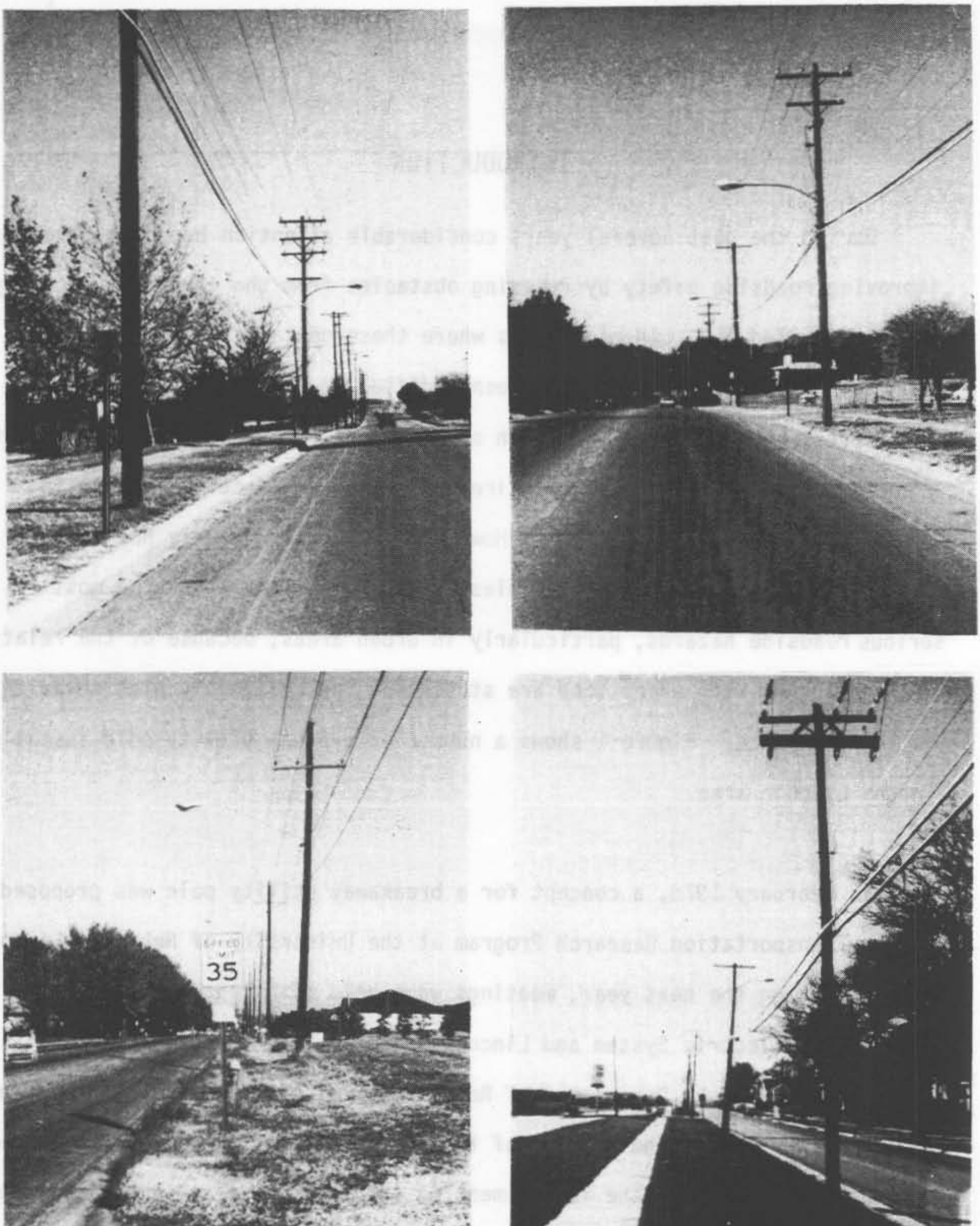


FIGURE 1. PHOTOGRAPHS OF TYPICAL UTILITY POLE FIELD INSTALLATIONS

The objective of this study was to determine the feasibility of the UNL breakaway utility pole concept. A series of scale-model, pendulum, and full-scale vehicle crash tests were conducted to (1) gain an understanding of the mechanics involved, (2) test the physical realizability of the concept, and (3) determine the degree to which it reduces impact severity. In addition, a computer simulation model was developed and validated with the data obtained from these tests. The model was then used to evaluate the performance of the concept for a variety of pole configurations and impact conditions. Based on the estimates of impact severity reduction from the computer simulations and full-scale tests, the potential cost-effectiveness of implementing the breakaway concept was determined.

This report documents the feasibility study of the UNL breakaway utility pole concept. Included are: (1) an analysis of utility pole accidents; (2) a description of the concept and its mechanics; (3) the procedures and results of the scale model, pendulum, and full-scale vehicle crash tests of the concept; (4) a description of the computer simulation model, its validation, and its application in evaluating the concept; and (5) a cost-effectiveness analysis of the concept. Also, a work plan is presented for future research needed for the further development and ultimate implementation of the concept.

BREAKAWAY UTILITY POLE CONCEPT

The breakaway utility pole design concept being developed by the University of Nebraska (UNL) consists of retrofitting existing poles to yield when struck by an errant vehicle at low speeds. As illustrated in Figure 2, the stub portion between the lower and upper breakaway joints will release when struck by an errant vehicle thereby allowing the vehicle to decelerate at a rate that will be tolerable to its occupants. After the vehicle knocks out the breakaway stub, the upper portion of the pole will fall and be held in an upright vertical position by the supporting wires. This final upright position of the pole requires that (a) the wires will stay attached to the insulators, and (b) the wires will have enough sag to allow the pole to fall without snapping the wires.

The breakaway joints are made by drilling a horizontal row of 1-in. diameter holes as shown in Detail "A" of Figure 2. A drilling jig is clamped to the pole to maintain correct alignment and spacing of the holes. The holes are drilled in the direction in which the majority of impacts will occur. This pattern and direction of holes will provide the minimum bending strength parallel to the wires and in the direction of impact, and the maximum bending strength perpendicular to the wires to carry the required ice and/or wind loads specified in the American National Standard Institute: National Electrical Safety Code (4).

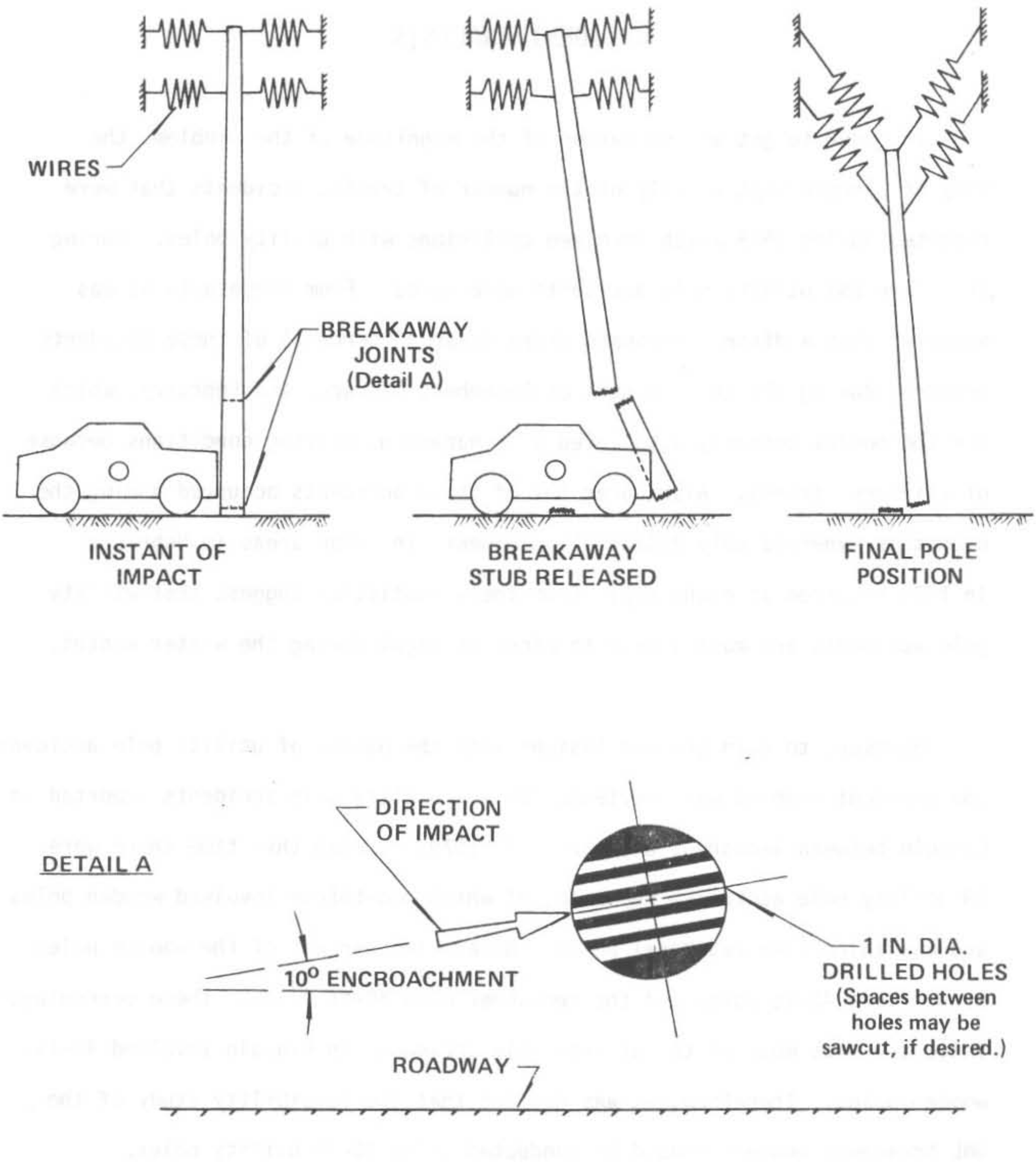


FIGURE 2. BREAKAWAY STUB CONCEPT FOR WOOD UTILITY POLES

ACCIDENT ANALYSIS

In order to get an indication of the magnitude of the problem, the City of Lincoln kept a tally of the number of traffic accidents that were reported during 1978 which involved collisions with utility poles. During this time 291 utility pole accidents were noted. From these data it was observed that a disproportionate share (over 40 percent) of these accidents occurred during the three months of December, January, and February, which are the months normally associated with hazardous driving conditions because of slippery streets. Also, over 50% of these accidents occurred during the nighttime, whereas only 33% of all accidents in urban areas in Nebraska in 1978 occurred at night (18). Thus these statistics suggest that utility pole accidents are most likely to occur at night during the winter months.

However, to gain greater insight into the nature of utility pole accidents, the accident reports were reviewed for all utility pole accidents reported in Lincoln between January 1 and April 15, 1979. During this time there were 59 utility pole accidents reported, of which two-thirds involved wooden poles and one-third involved metal poles. Ninety-two percent of the wooden poles struck were 40-ft poles and the remainder were 50-ft poles. These percentages indicated that most of the utility pole accidents in Lincoln involved 40-ft, wooden poles. Therefore, it was decided that the feasibility study of the UNL breakaway concept should be conducted using 40-ft utility poles.

Impact Conditions

In order to select a representative set of test conditions, an attempt was made to determine the speed and angle of vehicle impact for each wooden utility pole accident. However, these data were not recorded on the accident report forms. Therefore, to obtain at least some idea of the typical impact conditions, the posted speed limit at the location of each accident was noted and the angle of impact was estimated from the collision diagram shown on the accident report form. The frequency distributions of these conditions are shown in Table 1. Thus based on these distributions, it was decided that the UNL breakaway concept should be tested at impact speeds less than 35 mph and impact angles less than 30 degrees.

TABLE 1 - DISTRIBUTION OF IMPACT CONDITIONS

Impact Speed		Impact Angle	
Posted Speed Limit (mph)	Relative Frequency (%)	Angle (deg)	Relative Frequency (%)
≤ 25	26	Head On	31
30-35	60	5-30	62
≥ 40	14	> 30	7
	100		100

Severity of Impacts

The severity of the wooden utility pole accidents and that of collisions with fixed objects along streets in urban areas statewide are shown in Table 2. It is apparent from these data that wooden utility pole accidents have a higher than average accident severity.

TABLE 2 - SEVERITY OF FIXED OBJECT COLLISIONS

Object	Severity (%)			
	Fatal	Personal Injury	Property Damage Only	Total
Wooden Utility Poles in Lincoln	0	45	55	100
Fixed Object Collisions in Urban Areas Statewide (18)	1	35	64	100

In Table 3, the severity of the wooden utility pole accidents is presented with respect to speed and angle of impact, size of pole and weight of vehicle involved. As would be expected, these data indicate that higher severities are associated with higher impact speeds, larger poles, and lighter vehicles. And, the angle of impact does not seem to significantly affect the impact severity.

TABLE 3 -COMPARISONS OF WOODEN UTILITY POLE ACCIDENT SEVERITIES

Severity vs. Impact Speed:

Posted Speed Limit (mph)	Severity of Accident (%) Personal Injury	Property Damage	Total
≤ 30	30	70	100
35	50	50	100
≥ 40	60	40	100
Total	45	55	100

Severity vs. Impact Angle:

Impact Angle	Personal Injury	Property Damage Only	Total
Head On	42	58	100
5-30	46	54	100
> 30	33	67	100
Total	45	55	100

Severity vs. Pole Size:

Pole Size	Personal Injury	Property Damage Only	Total
40-ft	43	57	100
50-ft	67	33	100
Total	45	55	100

Severity vs. Vehicle Weight:

Vehicle Weight (lbs)	Personal Injury	Property Damage Only	Total
< 3,000	50	50	100
3,000-4,000	57	43	100
4,000-5,000	29	71	100
≥ 5,000	0	100	100
Total	45	55	100

Conclusion

From the results of this accident study, it is apparent that utility pole accidents are a serious problem in Lincoln, particularly at night during the winter months when they are most likely to occur. The 40-ft wooden utility pole is the type most commonly installed along arterial streets in Lincoln and consequently was the type most frequently struck. Thus this type of utility pole was selected for testing the UNL breakaway concept. Analysis of the most likely impact conditions indicated that the testing be conducted at impact speeds of 35 mph or less and impact angles of 30 degrees or less.

Compared to fixed object accidents in urban areas in Nebraska during 1978, wooden utility pole accidents in Lincoln had a higher than average severity. Also, as expected, the severity of these utility pole accidents generally increased with higher impact speeds, larger poles, and lighter vehicles.

DESIGN CRITERIA

The majority of utility poles in current use range from 25 to 105 ft. in height. A recent survey conducted by Labra (1) of the Southwest Research Institute showed that the 40 ft. Length Class 4 pole was the most common in use. The percentage breakdown of the survey by Labra on pole lengths are shown in Table 4. Based on this survey and the recommendations of Redding (2) of the Lincoln Electric System (LES) and McDevitt (3) of the Federal Highway Administration (FHWA), the 40 ft. Class 4 utility pole was selected for full-scale testing and evaluation.

The "typical" 40 ft. utility pole and wire arrangement used in this study and shown in Figure 3 were selected by LES. The pole has 3 top wires (type 336.4 KCM, 18/1) on a double cross-arm and 1 bottom neutral wire (2/0, 6/1) on the pole. The span length between poles is 150 ft. The loadings on the pole and wires are in accordance with the design specifications of the American National Standard: National Electric Safety Code (4). The specifications applicable to Nebraska are summarized in Table 5. The ANSI Code requires that a utility pole in Nebraska satisfy design loadings under (1) combined heavy ice + wind, and (2) extreme wind. The position of the applied loads are shown in Figure 3, whereas the computed magnitude of the applied loads are shown in Table 6.

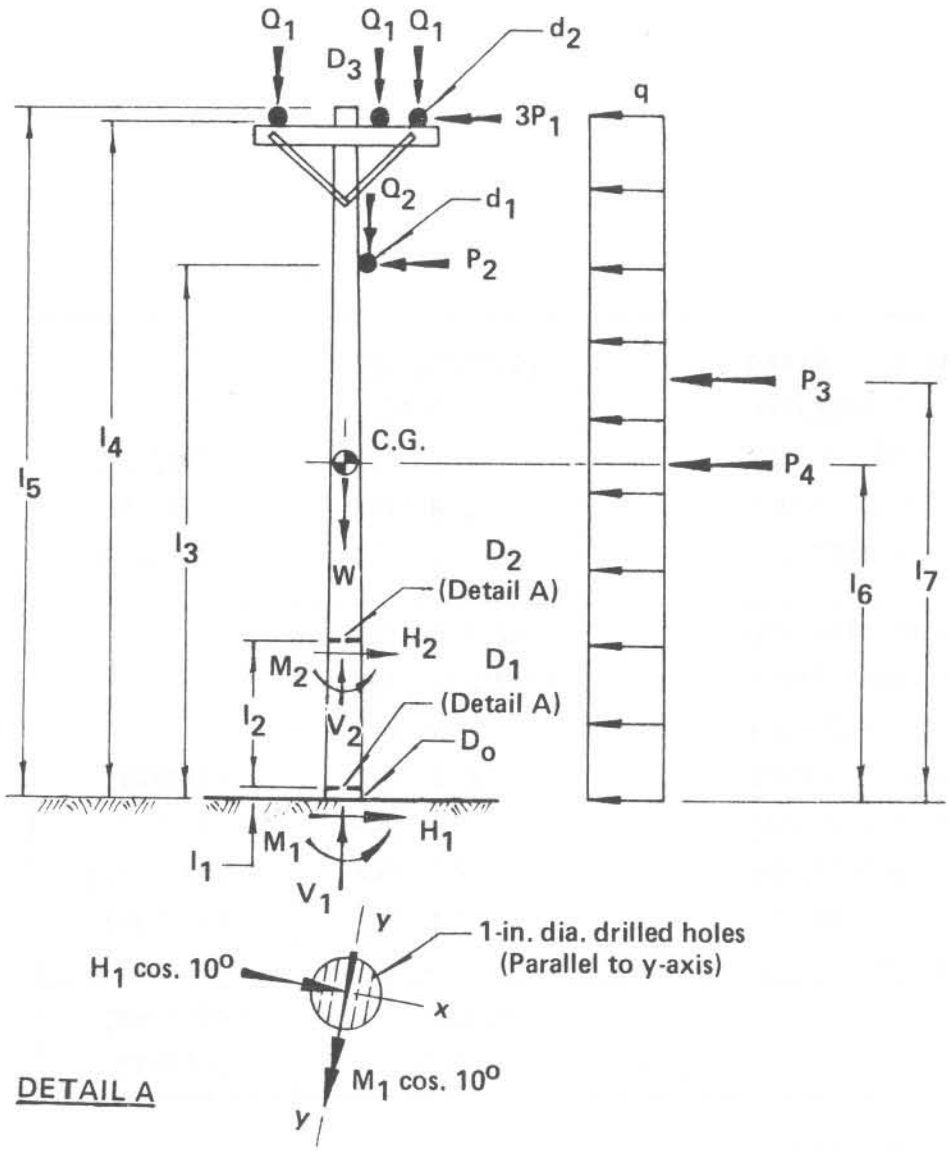
The locations of the lower and upper breakaway joints are shown in Figure 3. A cross-sectional view of the breakaway joint along with its mathematical properties (Eqs. 2a-e) are shown in Figure 4. As discussed

TABLE 4

SUMMARY OF UTILITY POLE LENGTHS

[after Labra (1)]

Pole Length (ft)	Percent in Use (%)	Cumulative Total (%)
25	0.2	0.2
30	20.7	20.9
35	21.0	41.9
40	29.6	71.5
45	16.6	88.1
50	7.6	95.7
55	0.7	96.4
60	0.6	97.0
65	0.7	97.7
70	0.6	98.3
75	0.6	98.9
80	0.5	99.4
85	0.4	99.8
90	0.1	99.9
100	Negl.	99.9
105	Negl.	99.9



DIMENSIONS				
WIRE DIAMETERS	[a]: d_1	=	0.684	in.
	d_2	=	0.447	in.
POLE DIAMETERS (min.)	: D_o [c]	=	10.7	in.
	D_1 [b]	=	10.6	in.
	D_2 [b]	=	9.9	in.
	D_3	=	6.7	in.
VERTICAL HEIGHTS	: l_1	=	0.5	ft.
	l_2	=	6.5	ft.
	l_3	=	27.0	ft.
	l_4	=	33.0	ft.
	l_5	=	34.0	ft.
	l_6	=	17.0	ft.
	l_7	=	20.5	ft.
AVERAGE SPAN LENGTH		=	150	ft.

NOTES: (a) Cross-Arm Wires (336.4 KCM, 18/1)
Neutral Wire (2/0, 6/1)
Wires fixed to insulators
(b) Locations of Breakaway Joints
(c) 6 ft. from butt (10% l_5 + 2)

FIGURE 3. TYPICAL 40 FT. CLASS 4 BREAKAWAY UTILITY POLE: DIMENSIONS, WIRE ARRANGEMENT, AND APPLIED LOADINGS

TABLE 5

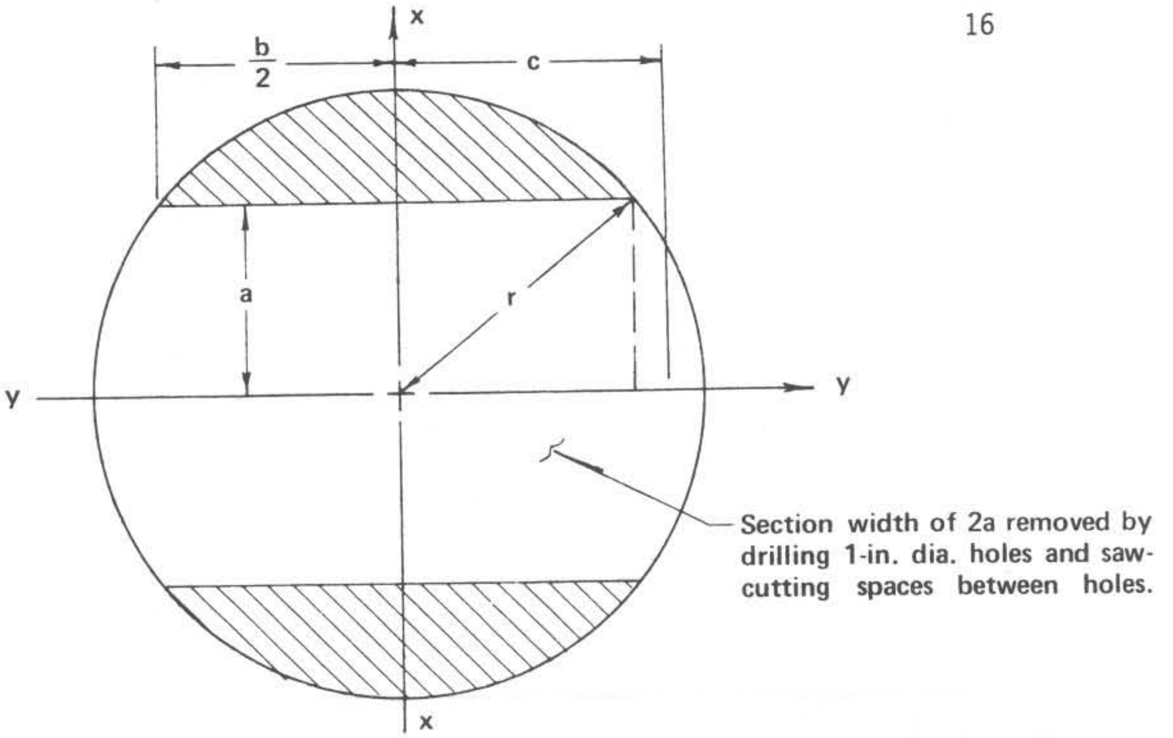
DESIGN SPECIFICATIONS FOR WOOD UTILITY POLES

ANSI (4)

LOADING CONDITION	CODE SECTION	I T E M	SPECIFICATIONS (Grade B)
Congined	250. B.	Radial Ice Thickness	0.50 in.
Ice + Wind	250. B.	Horizontal Wind Pressure	4 psf
Loading	250. B.	Ice Unit Weight	57 pcf
(Heavy)	251. B.3.	Conductor Load Constant	0.30 plf
	252. B.2.	Pole Shape Factor	1
	261. A.2.a(1)	Designated Fiber Stress (Yellow Pine)	8,000 psi
	261.A.2c(3)	Overload Capacity Factor	4
Extrene	250. C.	Horizontal Wind Pressure	16 psf
Wind	251. B.3.	Conductor Load Constant	0
Loading	252. B.2.	Pole Shape Factor	1
	260. C.	Overload Capacity Factor	1.0
	261.A.2.a(1)	Designated Fiber Stress (yellow Pine)	8,000 psi

TABLE 6. APPLIED MAGNITUDE OF LOADS

VARIABLE (Figure 2)	APPLIED LOADS(lb)	
	Ice + Wind Loading	Extreme Loading
P_1	85	140
P_2	70	90
P_3	75	300
P_4	95	385
Q_1	255	55
Q_2	160	25
W	620	620



COMBINED COMPRESSIVE STRESS

$$f_c = \left(\frac{M_{yy}}{S_{yy}} + \frac{V}{A}\right)(OL) \qquad \text{..........Eq. 1}$$

Where:
- M_{yy} = bending moment (in.-lb.)
- V = axial force (lb.)
- S_{yy} = section modulus (in.^{3})
- A = cross-sectional area (in.^{2})
- OL = Overload Factor
- f_c ≤ 8,000 p.s.i. (Yellow Pine)

Properties of Breakaway Joint

$$a = \sqrt{r^2 - \frac{b^2}{4}} \qquad \text{..........Eq. 2a}$$

$$c = \frac{1}{4}(d + b) \qquad \text{..........Eq. 2b}$$

$$I \doteq \frac{\pi}{64}d^4 - \frac{1}{12}(2c)(2a)^3 \qquad \text{..........Eq. 2c}$$

$$S \doteq \frac{\pi}{32}d^3 - \frac{8}{3}c\frac{a^3}{d} \qquad \text{..........Eq. 2d}$$

$$A \doteq \frac{\pi}{4}d^2 - 2a\,(2c) \qquad \text{..........Eq. 2e}$$

FIGURE 4. RELATIONSHIP BETWEEN COMBINED AXIAL AND BENDING STRESSES AND BREAKAWAY JOINT

earlier, the 1-in. dia. holes are drilled in the direction of impact (parallel to y-axis) and the space between the holes is saw cut. The combined compressive stresses due to the axial force and the bending moment are computed by Eq. 1 in Figure 4.

The required section modulus and shear area for the lower and upper breakaway joints are shown in Table 7. In all cases, the required (minimum) section modulus occurs under the heavy ice plus wind loading conditions. For all practical purposes, a drilling jig with 5-1in. dia. holes spaced 1 3/8 in. on centers (see Figure 5) would provide the minimum section modulus for both the lower and upper breakaway joints.

TABLE 7.

REQUIRED SECTION MODULUS AND SHEAR AREA AT LOWER AND UPPER BREAKAWAY JOINTS

VARIABLE (see Fig 3)	RESISTING FORCES (lb)		RESISTING MOMENT (lb-ft)		REQUIRED SECTION MODULUS (in^3)		REQUIRED SHEAR AREA(1) (in^2)	
	Ice + Wind Loading	Extreme Wind Loading	Ice + Wind Loading	Extreme Wind Loading	Ice + Wind Loading	Extreme Wind Loading	Ice + Wind Loading	Extreme Wind Loading
H_1	420	895	--	--	--	--	1.7	2.1
V_1	1,545	810	--	--	--	--	--	--
M_1	--	--	11,725	22,388	73.2(2)	33.9(4)	--	--
H_2	390	810	--	--	--	--	1.6	1.7
V_2	1,415	685	--	--	--	--	--	--
M_2	--	--	9,030	17,770	55.8(3)	27.0(5)	--	--

Notes: (1) Ultimate Shearing Stress taken as 1,000 psi

(2) Refer to Figure 2 : d = 10.60 in. ; r = 5.30 in.
a = 3.33 in. ; b = 8.25 in.; c = 4.71 in.
A = 25.5 in.^{2} ; f_c = 7,935 psi

(3) Refer to Figure 2 : d = 9.90 in. ; r = 4.95 in.
a = 3.23 in. ; b = 7.50 in.; c = 4.35 in.
A = 20.8 in.^{2} ; f_c = 8,040 psi

(4) Refer to Figure 2 : d = 10.60 in. ; r = 5.30 in.
a = 4.28 in. ; b = 6.25 in.; c = 4.21 in.
A = 16.17 in.^{2}; f_c = 7,980 psi

(5) Refer to Figure 2 : d = 9.90 in. ; r = 4.95 in.
a = 4.01 in. ; b = 5.80 in.; c = 3.93 in.
A = 13.94 in.^{2}; f_c = 7,950 psi

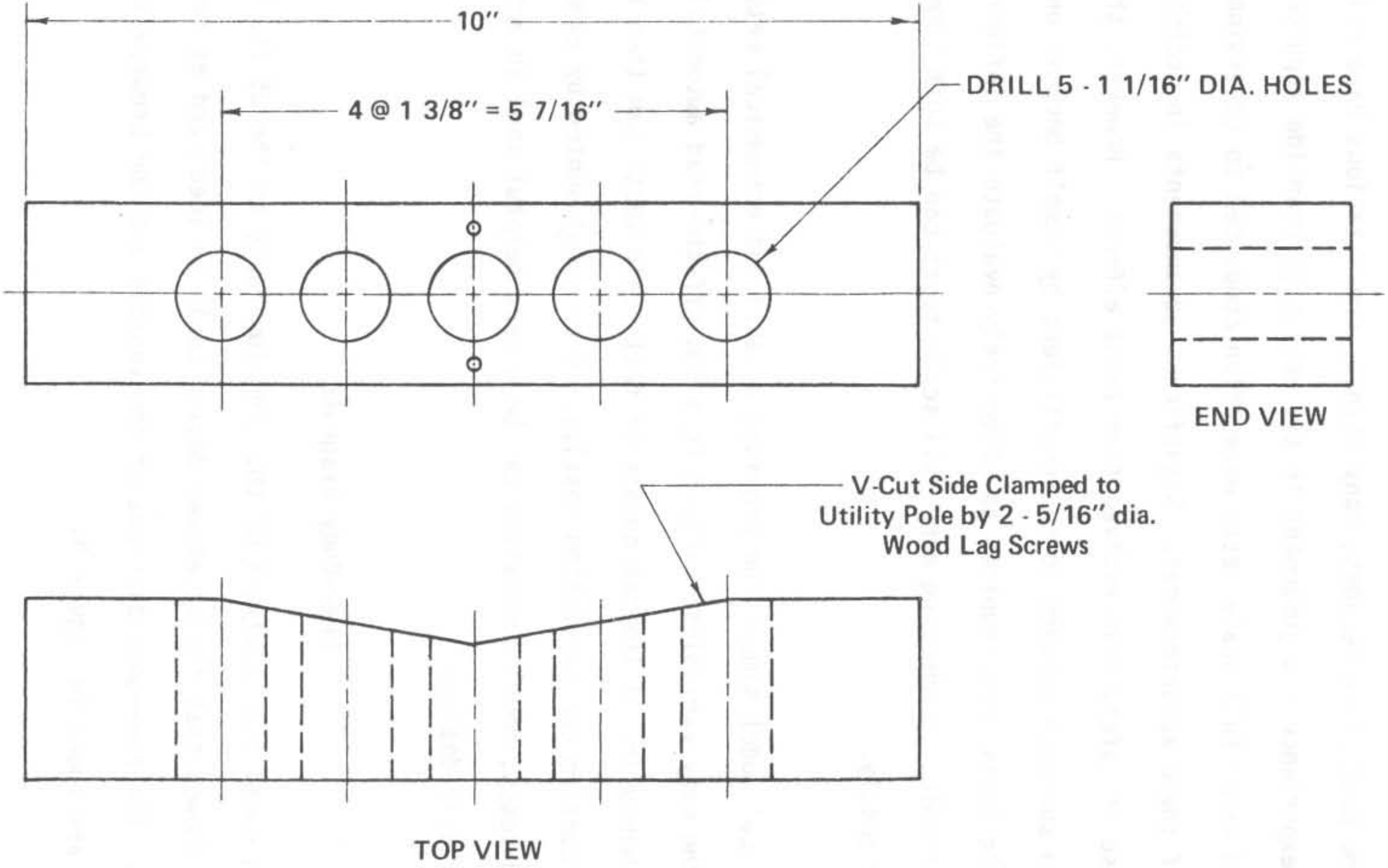


FIGURE 5. DRILLING JIG (4 X 4 X 10 D.F. WOOD BLOCK)

COMPUTER MODEL

During the past three decades, many highway organizations have relied heavily upon experience and judgement in the design of roadside appurtenances; and, trial and error full scale tests were often conducted to determine the feasibility of these appurtenances. Significant advancements in technology and an increase in safety have evolved from these efforts. However, this type of design approach appears to be insufficient by itself because one or more full scale tests were required to effectively evaluate the influence of any one variable. Conducting many full scale tests can be both time consuming and costly.

Mathematical model simulation provides a rapid and economical method to investigate the many variables involved in a run-off-the-road automobile collision or maneuver. A limited number of full scale tests can then be conducted to confirm the simulation results. When supplemented by experience, judgement and tests, model simulation can be a very helpful tool in achieving efficient and safe designs.

Free-Body-Diagrams

The high-speed film analysis of the pendulum tests on the 25 ft. breakaway utility pole showed that the breakaway design could be idealized as two rigid bodies. The free-body-diagrams of the vehicle and the breakaway utility pole are shown in Figure 6.

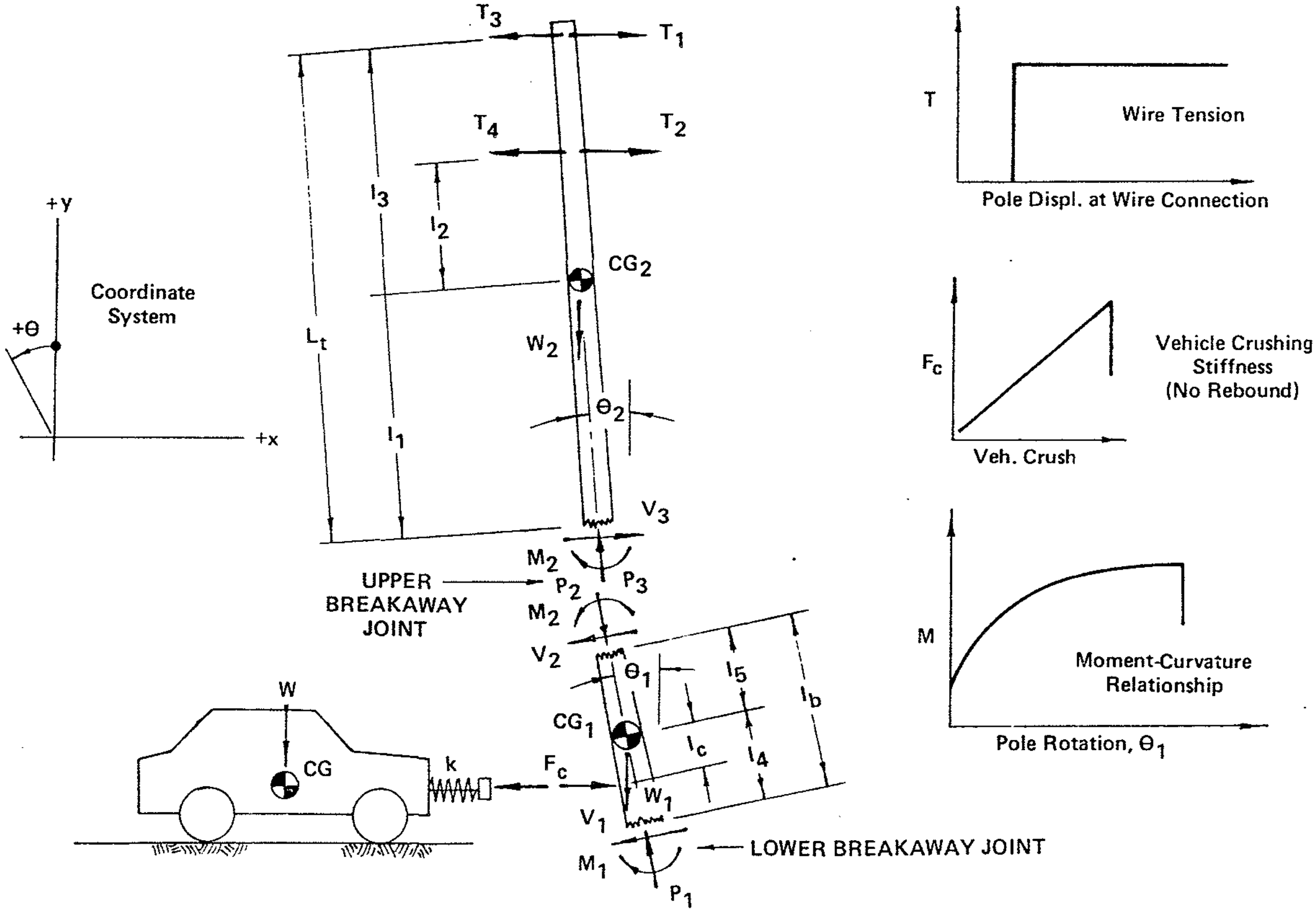


FIGURE 6. FREE BODY DIAGRAMS OF VEHICLE AND UTILITY POLE

Vehicle

The vehicle was idealized by a rigid mass and a linear spring. The spring simulates the front-end crushing of the vehicle. The spring constant (k = 10W) used in this study for a standard size vehicle (4,500 lb) was validated by Post and Martinez (5) on overhead sign bridge breakaway supports. No provisions were made to monitor secondary contacts of the lower and upper portions of the pole after breaking away with the upper portions of the vehicle (hood, windshield, top, etc). The model can be refined to include secondary contacts in any future work.

Utility Pole

The utility pole was idealized by two rigid bodies: the lower rigid body represents the portion of the pole between the lower and upper breakaway joints; whereas, the upper rigid body represents the portion of the pole above the upper breakaway joint. The effects of the tensile forces in the wire were considered when the rotational displacements of the pole were large enough to overcome some sag in the wires. The bending moments at the breakaway joints were treated as a non-linear function of the pole rotational displacements. The shearing forces, which are complex and difficult to predict with any degree of accuracy, were considered to be proportional to the horizontal displacements of the breakaway joint. A more indepth discussion on the force-displacement relationships are presented later in the section, entitled "Validation of Computer Model".

Differential Equations of Motion

The differential equations of motion developed in this study were solved using the numerical program, Continuous System Modeling Program, made available by IBM. The equations developed follows.

Lower Rigid Body

$$\sum F_x = m\ddot{x}$$

$$F_c - V_1\cos\Theta_1 - P_1\sin\Theta_1 - V_2\cos\Theta_1 + P_2\sin\Theta_1 = \frac{W_1}{g}\ddot{x}_1 \qquad \text{--Eq. 3a}$$

$$\sum F_y = m\ddot{y}$$

$$-W_1 - V_1\sin\Theta_1 + P_1\cos\Theta_1 - V_2\sin\Theta_1 - P_2\cos\Theta_1 = \frac{W_1}{g}\ddot{y}_1 \qquad \text{--Eq. 3b}$$

$$\sum M = I\ddot{\Theta}$$

$$F_c\ell_c - V_1\ell_4 - M_1 + V_2\ell_5 + M_2 = I_{cg_1}\ddot{\Theta}_1 \qquad \text{--Eq. 3c}$$

Upper Rigid Body

$$\sum F_x = m\ddot{x}$$

$$V_3\cos\Theta_2 - P_3\sin\Theta_2 + T_1 + T_2 - T_3 - T_4 = \frac{W_2}{g}\ddot{x}_2 \qquad \text{--Eq. 4a}$$

$$\sum F_y = m\ddot{y}$$

$$-W_2 + V_3\sin\Theta_2 + P_3\cos\Theta_2 = \frac{W_2}{g}\ddot{y}_2 \qquad \text{--Eq. 4b}$$

$$\sum M = I\ddot{\Theta}$$

$$V_3\ell_1 - M_2 - T_1\ell_3 - T_2\ell_2 + T_3\ell_3 + T_4\ell_2 = I_{cg_2}\ddot{\Theta}_2 \qquad \text{--Eq. 4c}$$

Moment-Rotation Relationship

$$M_2 = K(\Theta_1 - \Theta_2) \qquad \text{--Eq. 5}$$

Force-Displacement Relationships

$$V_2\cos\Theta_1 - P_2\sin\Theta_1 = V_3\cos\Theta_2 - P_3\sin\Theta_2 \qquad \text{--Eq. 6a}$$

$$V_2\sin\Theta_1 + P_2\cos\Theta_1 = V_3\sin\Theta_2 + P_3\cos\Theta_2 \qquad \text{-- Eq. 6b}$$

SCALE MODEL TESTS

Scale model tests of the UNL breakaway utility pole concept were conducted to gain a physical sense of the failure mechanism involved. In these tests, the vehicle was a one-twelfth size, toy pickup truck, and a 1" x 40" wooden dowel was used to represent a 40-ft utility pole. A number of one-eighth inch holes were drilled in the dowel at distances of one-half inch and seven inches above its base to simulate the lower and upper breakaway joints. A wire was attached to the top of the dowel and held taut during the tests to simulate the effects of power lines on a utility pole. The vehicle was placed on an incline plane positioned in front of the dowel. It was released at a point on the plane selected to simulate an approximate impact speed of 20 mph.

Several tests were conducted and filmed with high-speed cameras. Analysis of the high-speed film taken of these tests provided the following observations:

(1) The bending moment at the upper breakaway joint appeared to be sufficient to cause failure.

(2) It appeared to be highly desirable to have the upper joint fail first so that the stub can be pushed ahead and downward in front of the vehicle instead of being projected upward and into the windshield of the vehicle.

(3) To insure the proper failure mode, it is important that the base of the pole be rigid.

The observations made during the scale model tests resulted in a greater understanding of the failure mechanism of the breakaway concept, and thus provided a basis for the subsequent testing and modeling of the concept.

PENDULUM TESTS

Pendulum tests were conducted on 25 ft, Class 7 and 9 Southern Yellow Pine utility poles provided by Lincoln Telephone and Telegraph (LT&T). LT&T is currently in the process of replacing existing overhead lines with buried cable. The poles received were therefore in a weathered condition similar to poles that would be retrofitted with breakaway joints.

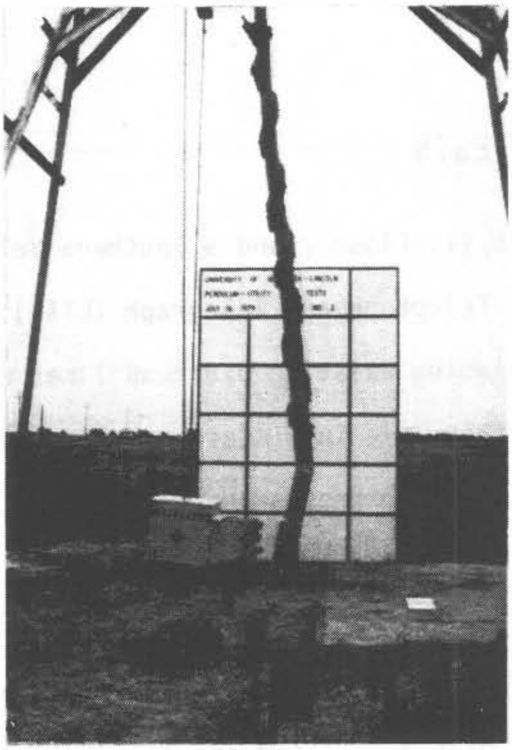
Description of Site

The pendulum tests were conducted at the University of Nebraska Mead Agricultural Research Field Laboratory which is located approximately 30 mi. NNE of Lincoln. The pendulum and hardware were provided by the Department of Agricultural Engineering.

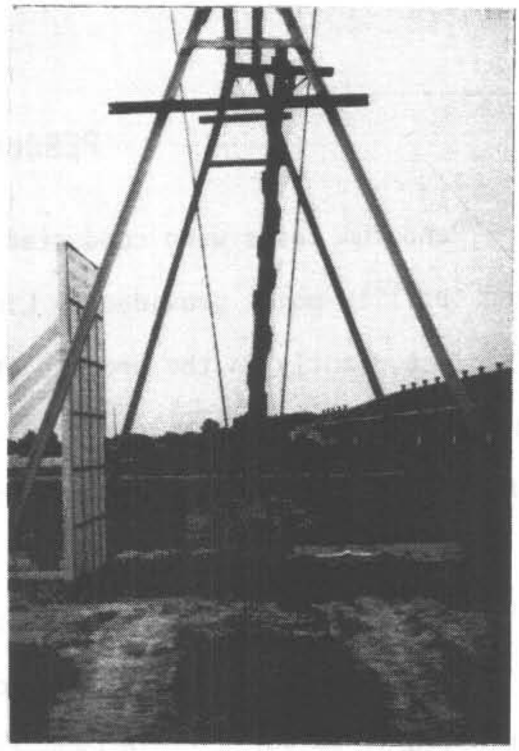
Description of Testing Apparatus

Photographic views of the pendulum mass and frame are shown in Figure 7. The 21 ft. high pendulum frame was built by the Department of Agricultural Engineering for the testing of roll bars on farm tractors. The entire pendulum frame was built using steel rail sections. The ends of the pendulum frame are A-shaped to accomodate the large swings of the pendulum up to heights of 15 ft. (21 mph).

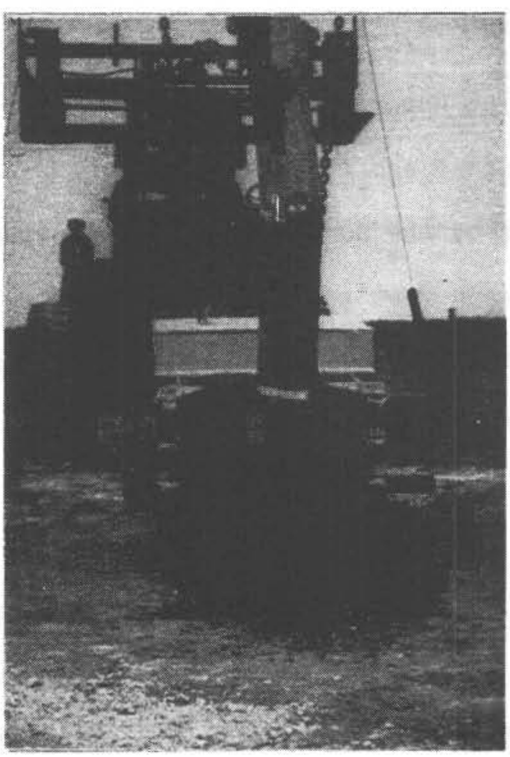
The pendulum mass weighed 4,500 lbs and consisted of a square steel box filled with lead. The pendulum was supported by two steel chains which could be adjusted to any length. A pendulum nose was added in this utility pole study to simulate the crushing effects of a vehicle bumper and front-end.



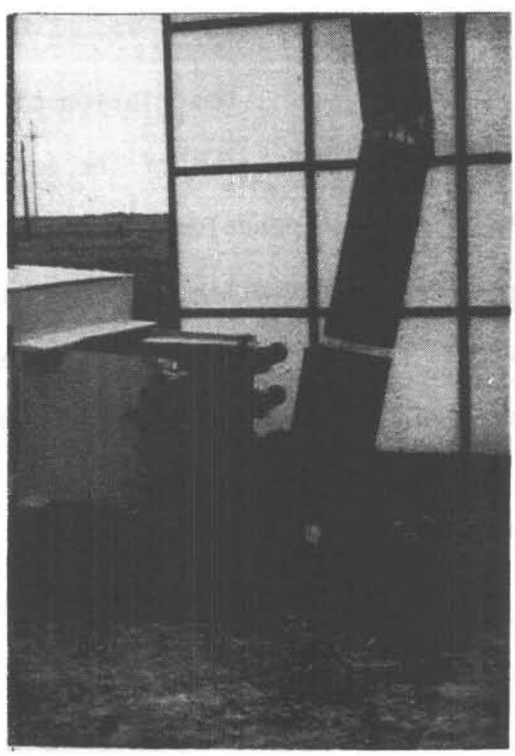
(a)



(b)



(c)



(d)

FIGURE 7. PHOTOGRAPHS OF PENDULUM TEST NO. 2

The nose provided for a 12-in. maximum deflection. Two and one-half (2 1/2) inch extra heavy pipe, simply supported with a 30-in. span, and sawcut to 3/8 of an inch at the third points were used in the nose to simulate the crushing characteristics of the vehicle front-end. Three pipes were used for each test with a vertical spacing of 6 inches. The load-deflection characteristics of each sawcut pipe is shown in Figure 8. The nose device added about 150 lbs to the pendulum mass.

As shown in Figure 7, a large fork-lift was used to pull-back the pendulum. A quick type release device was used to release the pendulum.

Dimensional Analyses

In order to determine the feasibility of the breakaway utility pole concept, it was decided to perform a number of pendulum tests utilizing the technique of scale modeling. The use of scale models as an aid in evaluation of design features has a long history and is well documented. Before results from the scale model can be of any use, it was necessary to derive the laws of similtude using dimensional analysis. The variables included in the dimensional analyses are shown in Table 8.

A number of dimensionless products, also called Π-terms, composed of the variables shown in Table 8 are found. The number of Π-terms (i) formed for a given number of variables are equal to the number of variables (j) minus the number of fundamental units (k) that describe the variables. That is, $i=j-k$. In this case the number of variables is $j=9$, and the number of fundamental units (Mass, Length, and Time) are $k=3$. To insure similitude between the model and the prototype, the Π-terms for the model must equal the Π-terms for the prototype. The Π-terms derived are shown in Equations (7a-f).

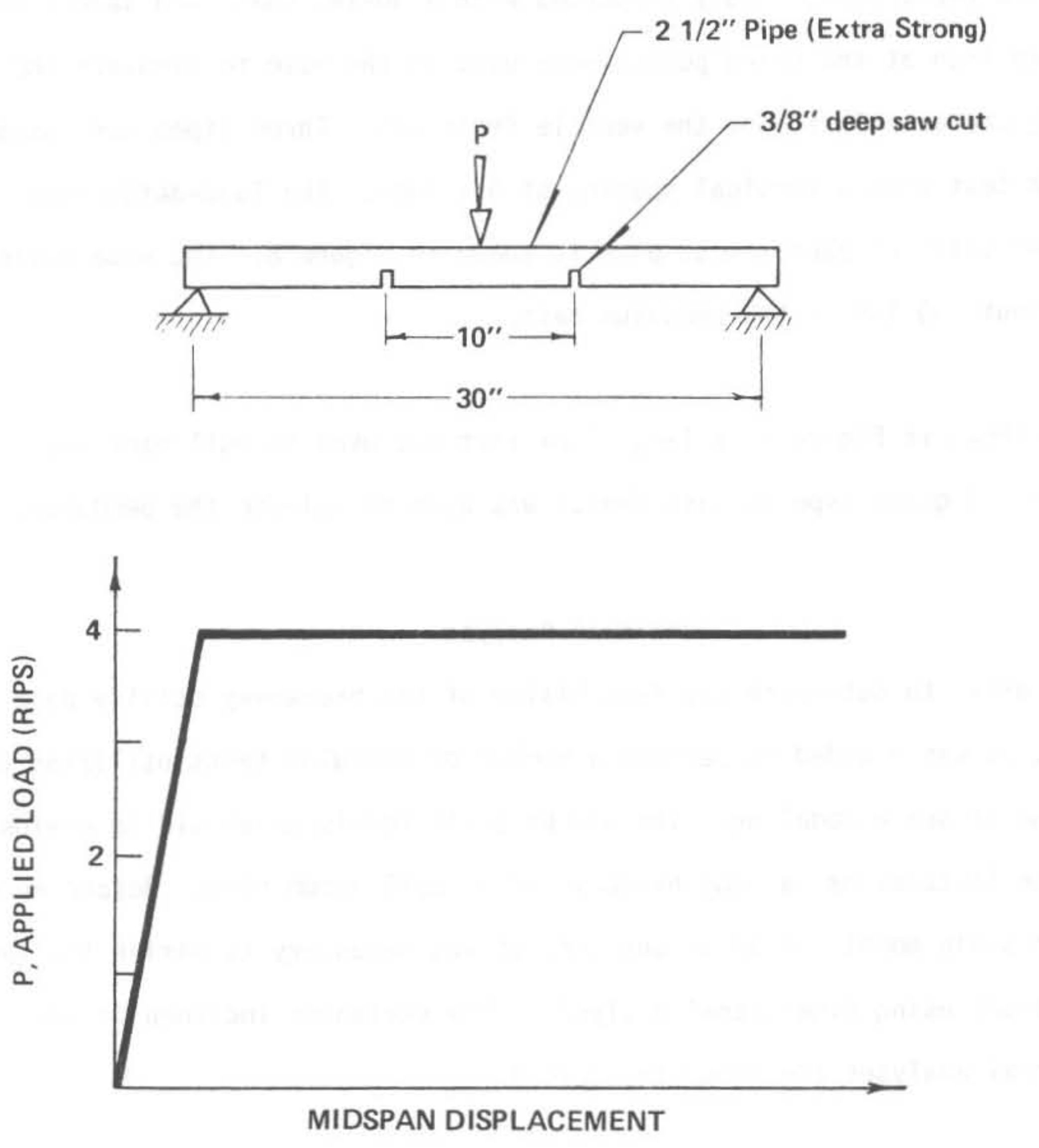


FIGURE 8.
PENDULUM FRONT-END CRUSHING STIFFNESS
(SINGLE PIPE)

TABLE 8. DIMENSIONAL ANALYSES OF VARIABLES

VARIABLE	VARIABLE DESIGNATION	DIMENSION
Mass of pole	W	(M)
Stress in pole	T	$(ML^{-1}T^{-2})$
Height of pole above ground	L	(L)
Modulus of elasticity of pole	E	$(ML^{-1}T^{-2})$
Section modulus of pole	S	(L^3)
Arbitrary length term	D	(L)
Mass of auto	M	(M)
Crush stiffness of auto	K	(MT^{-2})
Velocity of auto	V	(LT^{-1})

Dimensionless Products (Π-Terms)

$$\Pi_1 = \frac{W}{M} \qquad \text{--Eq. 7a}$$

$$\Pi_2 = \frac{L}{D} \qquad \text{--Eq. 7b}$$

$$\Pi_3 = \frac{WV^2}{S(E)} \qquad \text{--Eq. 7c}$$

$$\Pi_4 = \frac{L^3}{S} \qquad \text{--Eq. 7d}$$

$$\Pi_5 = \frac{K^3}{S(E^3)} \qquad \text{--Eq. 7e}$$

$$\Pi_6 = \frac{T}{E} \qquad \text{--Eq. 7f}$$

The 21 ft. height of the pendulum frame used for the testing made it necessary to limit the size of the utility poles tested to 25 ft. The geometry relationships for modeling were thus set as follows:

$$\frac{L_p}{L_m} = \frac{34 \text{ ft}}{20 \text{ ft}} \qquad \text{--Eq. 8}$$

$$= 1.7$$

where: p = subscript refers to 40 ft prototype to be used in full-scale testing

m = subscript refers to pendulum model

One term that caused a problem, was Π_1. This term shows that the mass of the 25 ft. pole must be equal to the mass of the 40 ft. pole when the mass of the prototype and model are the same, which is the existing situation. To satisfy this requirement 225 lbs of heavy link chain was carefully wound around the 25 ft. poles as shown in Figure 7. This appeared to be the best method to obtain equal distribution of weight along the pole. Due to the length of chain available, the Π_1 term could not be satisfied completely. The calculations for the added chain mass to the pole follows:

$$(\Pi_1)_p = (\Pi_1)_m \qquad \text{--Eq. 9a}$$

$$(\tfrac{W}{M})_p = (\tfrac{W}{M})m \qquad \text{--Eq. 9b}$$

$$\frac{W_p}{W_m} = \frac{M_p}{M_m} \text{ . . . . Equal Unity} \qquad \text{--Eq. 9c}$$

$$= \frac{750 \text{ lbs}}{300 \text{ lbs + Wt of Chain}}$$

$$= \frac{750 \text{ lbs}}{300 \text{ lbs} + 225 \text{ lbs}}$$

$$= 1.42 \text{ . . . . close to unity}$$

Determination of the height of the breakaway joints can be obtained from the Π_2 term. The location of the lower and upper joints with respect to the ground for the prototype were 0.5 ft and 7.0 ft, respectively. Calculations for computing the height of the breakaway joints for the pendulum testing follow:

$$\Pi_2 = \frac{L}{D} \qquad \text{--Eq. 10a}$$

where: D_1 = distance from ground to lower joint

D_2 = distance from ground to upper joint

$$(\Pi_2)_p = (\Pi_2)_m \qquad \text{--Eq. 10b}$$

$$\frac{L_p}{(D_1)_p} = \frac{L_m}{(D_1)_m} \qquad \text{--Eq. 10c}$$

thus,

$$(D_1)_m = \frac{L_m}{L_p}(D_1)_p = \frac{20}{34}(0.5) \qquad \text{--Eq. 10d}$$

$$= 0.29 \text{ ft } (3\ 1/2\text{-in.})$$

and similarly,

$$(D_2)_m = \frac{L_m}{L_p}(D_2)_p = \frac{10}{34}(7.0) \qquad \text{--Eq. 10e}$$

$$= 4.12 \text{ ft}$$

The impact speed for the pendulum model can then be determined by use of the Π_3 term as follows:

$$\Pi_3 = \frac{WV^2}{S(E)} \qquad \text{--Eq. 11a}$$

$$\left(\frac{WV^2}{SE}\right)_p = \left(\frac{WV^2}{SE}\right)_m \qquad \text{--Eq. 11b}$$

thus,

$$V_m = [(\frac{W_p}{W_m})(\frac{S_m}{S_p})(V_p^2)]^{\frac{1}{2}} \qquad \text{--Eq. 11c}$$

Pendulum Testing

A dimensional analysis was performed on the 25 ft poles in an attempt to model these poles as 40 ft class 4 utility poles impacted by a 4500 lb. vehicle. Due to the varying nature of material properties, and the possible presence of pole defects, the results from the modeling process may cause a deviation from predicted results. Similar poles, with approximately the same diameters were grouped into test series to improve the consistency of results.

A 4500 lb. vehicle with an impact speed of 20 mph was used as the prototype condition. Utilizing the modeling relations that were derived earlier, the model test parameters were determined knowing the desired parameters for the prototype. The computed parameters are shown in Table 9.

TABLE 9. PROTOTYPE AND MODEL PARAMETERS

Modifications	Prototype 40 ft Pole	Modeled 25 ft Pole	Actual 25 ft Pole
Lower B/A joint height	6 in.	3.5 in.	3 in.
Upper B/A joint height	7.0 ft.	4.11 ft.	4.0 ft.
Vehicle Velocity	20 mph	9.45 mph	9.95 mph
Total pole weight (includes added weights)	800 lbs.	800 lbs.	≅ 500 lbs.
Added weight of chains	---	---	240 lbs.

The Π terms developed in the dimensional analysis were used to determine the prototype section properties shown in Table 10.

TABLE 10. SECTION PROPERTIES FOR PENDULUM POLE TESTS

Section Properties	25 ft. Pole	40 ft Pole
Section modulas perpendicular to wires, upper hinge	11.3 $in.^3$	55 $in.^3$
Section modulas perpendicular to wires, lower hinge	19.4 $in.^3$	95 $in.^3$
Shear area, upper hinge	5.9 $in.^2$	15.6 $in.^2$
Shear area, lower hinge	10.3 $in.^2$	29.8 $in.^2$

The hole patterns of the breakaway joints that will provide the section modulus and shear area properties given in Table 10 are shown in Figure 9. The patterns were made by drilling 1-in. diameter holes and then saw cutting the spaces between the holes. A 4 x 4-in. wooden drilling jig, which was clamped to the pole with two lag screws, was used to maintain correct alignment and spacing of the holes.

High-Speed Film Analysis

One high-speed camera, described in Table 11, was used in the pendulum study. The camera was located perpendicular to the path of the pendulum and approximately 50 ft. from the pole. The film was analyzed by a Vanguard Motion Analyzer, described in Table 11.

The complete data reduction and analyses of the high-speed film was conducted on Pendulum Test No. 7. This data and analysis is presented in Appendix C.

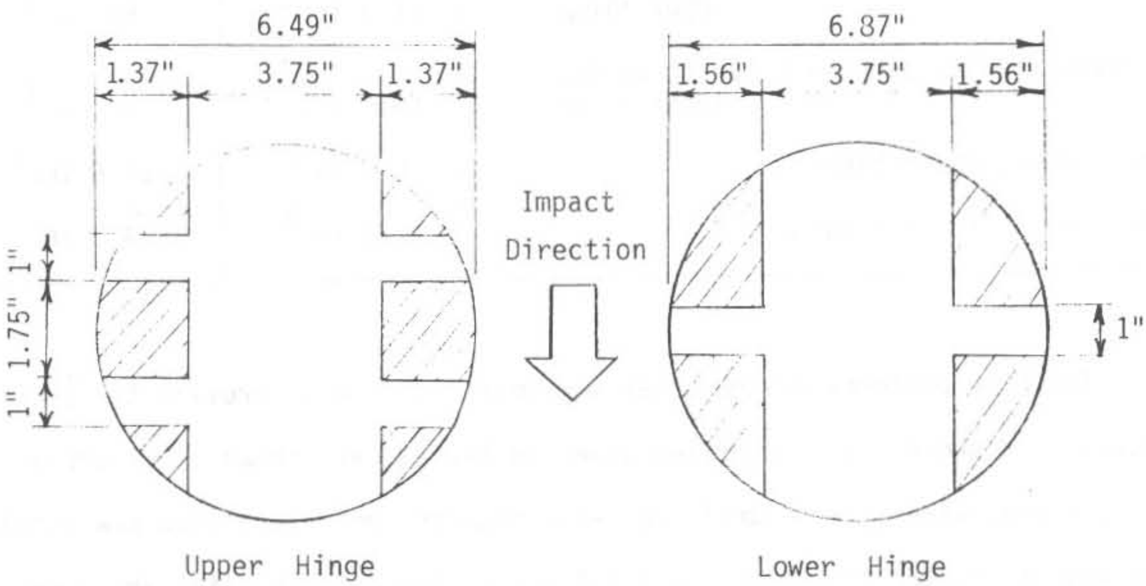


FIGURE 9. BREAKAWAY JOINT HOLE PATTERNS FROM PENDULUM TESTS

TABLE 11

PHOTOGRAPHIC ANALYSIS EQUIPMENT USED

Equipment Description	Pendulum Tests	Full-Scale Test
1. LoCam model 50-003 high speed Camera. Film rate is variable to 500 fm./sec. Actual film speed = 480 fm./sec.	X	X
2. Eastman Kodak high speed Camera, type III. Film rate is variable to 3000 fm./sec. Actual film speed = 900 fm./sec.		X
3. Vanguard Motion Analyzer model C-11P with M16CP projection head. Frame rate is variable to 30 fm./sec. A model 524-C digitizer built at the University of Iowa to input data to a computer is also linked up.	X	X

Due to lack of time and funds and also because of the uncertainties encountered in dimensional analyses modeling, no attempt was made to validate the results of the high-speed film analyses with the computer model program.

Sequence photographs of the high-speed film intervals of 2 msec are shown in Figure 10. In this test, it can be seen that the upper breakaway joint failed first at about 4 msec, whereas, the lower joint failed shortly later at about 6 msec. This mode of failure will allow the vehicle to push the breakaway stub ahead and down which would perhaps be preferable to the other mode of failure whereby the lower joint would fail first with the possibility of the stub striking the windshield.

Photographic views of Test No. 2 is shown back in Figure 7. In this test, the ground was very wet from a rain storm of the previous day, and as a result, most of the energy of the pendulum was used up in plowing the pole ahead approximately 1 ft. in the soil. It appears that this would have been a successful test if the ground had not been wet.

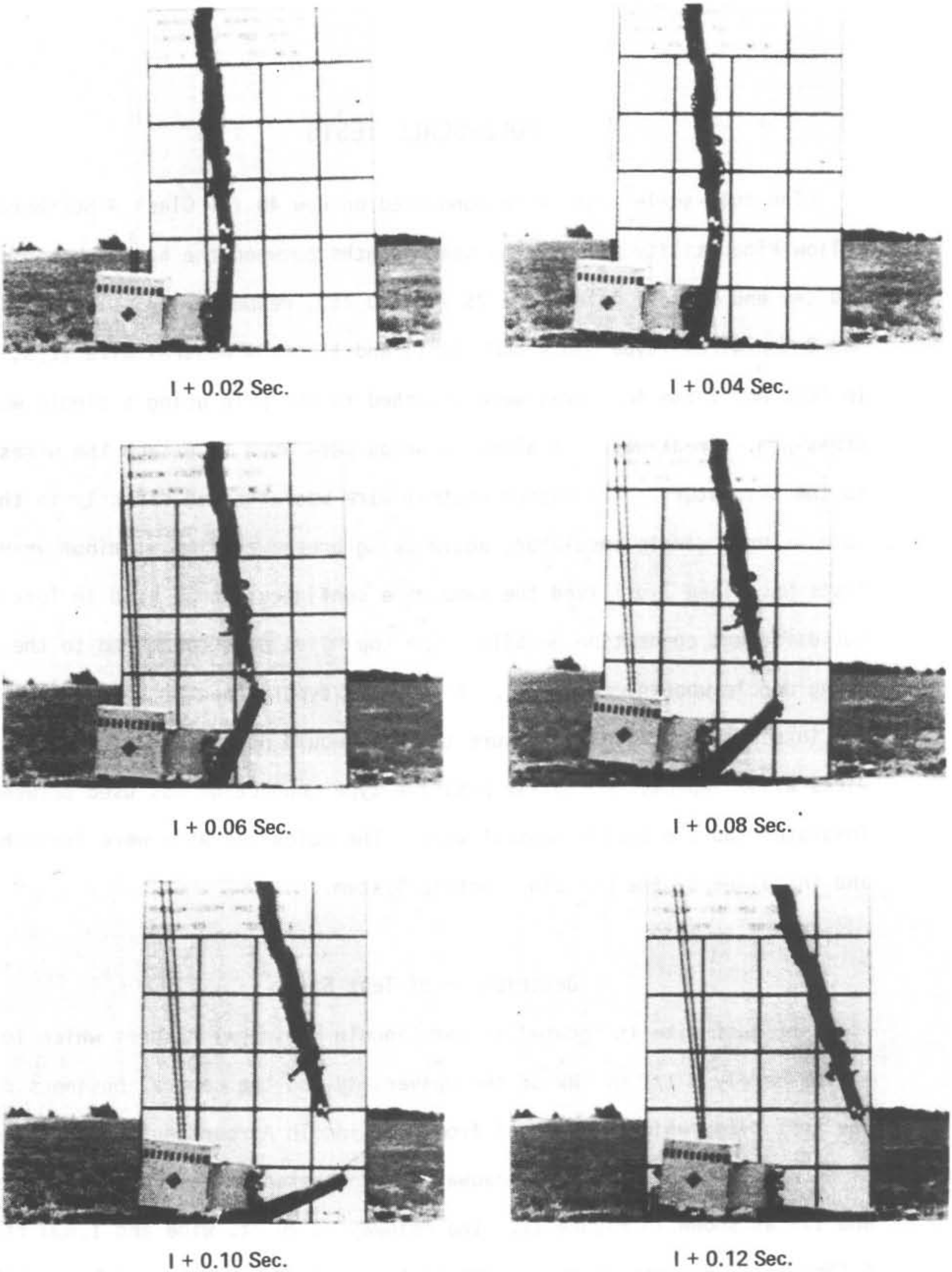


FIGURE 10. HIGH-SPEED FILM OF PENDULUM - TEST

FULL-SCALE TESTS

The full-scale tests were conducted on new 40 ft. Class 4 Southern Yellow Pine utility poles. The span lengths between the breakaway pole and the end support poles were 75 and 100 ft., respectively. The poles had 2 top wires (type 336.4 KCM, 18/1) and 1 bottom neutral wire (2/0, 6/1). In Test No. 1 the top wires were attached to the pole using a single wooden cross-arm. Breakaway flat aluminum wraps were used to attach the wires to the insulators. The bottom neutral wire was attached directly to the pole using a single insulator, again using breakaway flat aluminum wraps. Tests No. 2 and 3 utilized the same wire configuration as used in Test No. 1 but different connection details. The top wires were connected to the pole using double wooden cross-arms. A positive type connector between the wires and insulators was used to insure the pole would not breakaway from the wires after impact. A similar positive type connection was used between the insulator and the bottom neutral wire. The poles and wire were furnished and installed by the Lincoln Electric System.

Description of Test Site

The test site is located at the Lincoln Municipal Airport which is approximately 3 1/2 mi. NW of the University and the central business district. The test site, which was leased from the Lincoln Airport Authority, consists of an old abandoned concrete roadway located between the ends of runways 14 and 17R as shown in Figure 11. The roadway is 20 ft. wide and 1,800 ft. long. A "Notice of Proposed Construction or Alteration" was filed with the FAA because the height of the utility poles exceeded the 100 to 1 imaginary surface.

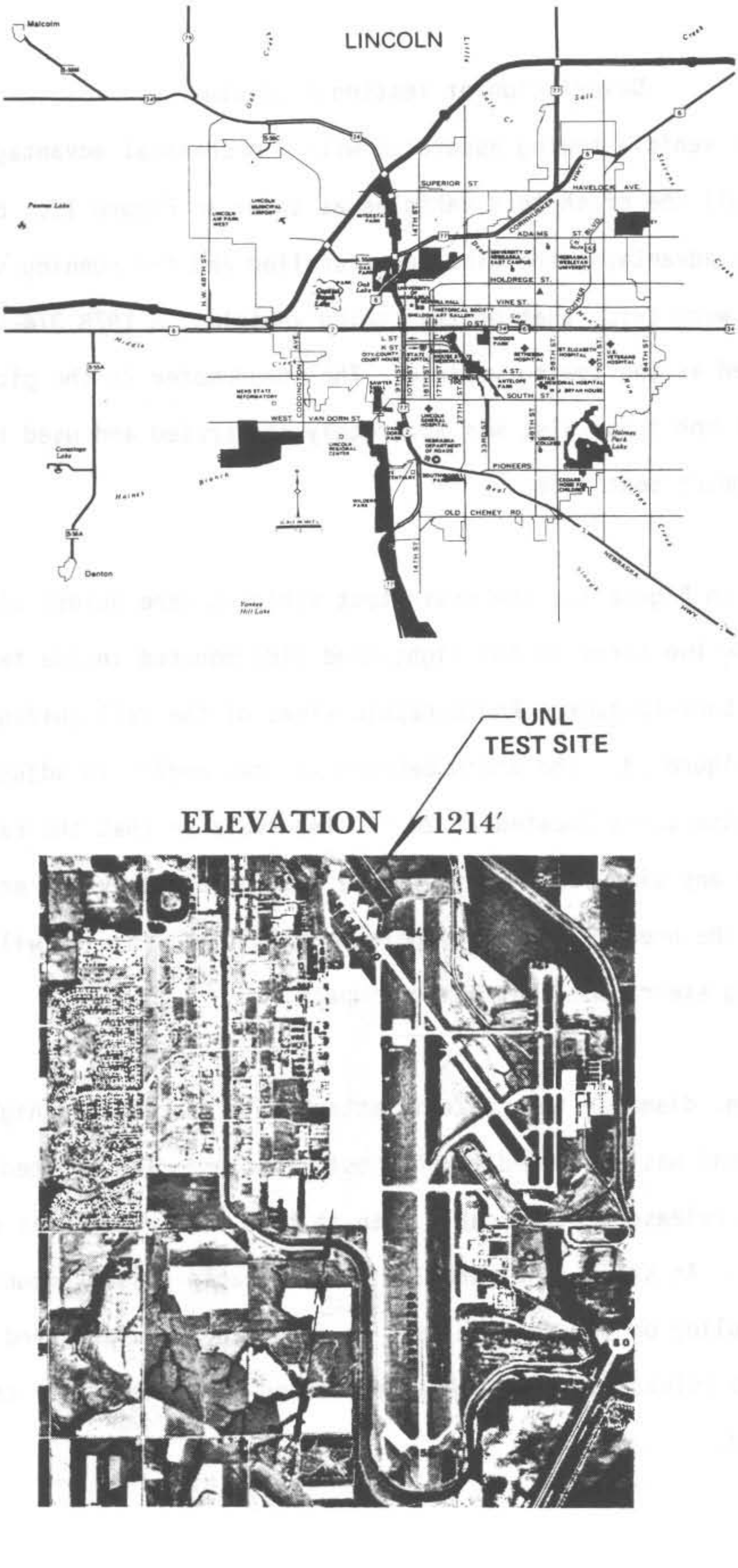


FIGURE 11. LOCATION OF FULL-SCALE TEST SITE

Description of Testing Apparatus

A reverse vehicle towing apparatus with a mechanical advantage of 2 to 1 was used to pull the crash test vehicles as shown in Figure 12. Because of the mechanical advantage, the distance travelled and the running speed of the test vehicles were twice that of the towing vehicle. A 1978 3/4-ton Dodge Pickup was used as the towing vehicle. The speedometer in the pickup, which is marked at 1 mph intervals, was accurately calibrated and used to obtain the desired impact test speed.

As shown in Figure 12, the crash test vehicles were guided along a rail system with the two tires on the right-hand side mounted inside two steel angles placed back-to-back. Photographic views of the rail guidance system are shown in Figure 13. The width between the two angles is adjustable at the slotted connections located at 20 ft. intervals so that the rail system can accomodate any size vehicle tire. The rail guidance system ends 20 ft. in advance of the breakaway utility pole so that test vehicles will be in a free-wheeling steer mode just before impact.

The 1/4-in. diameter tow cable is attached to a breakaway high-strength slotted bolt that was connected to the test vehicles. The slotted bolt will break away and release the tow cable when it hits a trip-bar that was mounted to the roadway. As shown in Figure 12, the tow cable passes around four pulleys (one pulley on tow vehicle) and is connected to a dead-end anchor. The trip-bar to release the tow cable is mounted near the end of the rail guidance system.

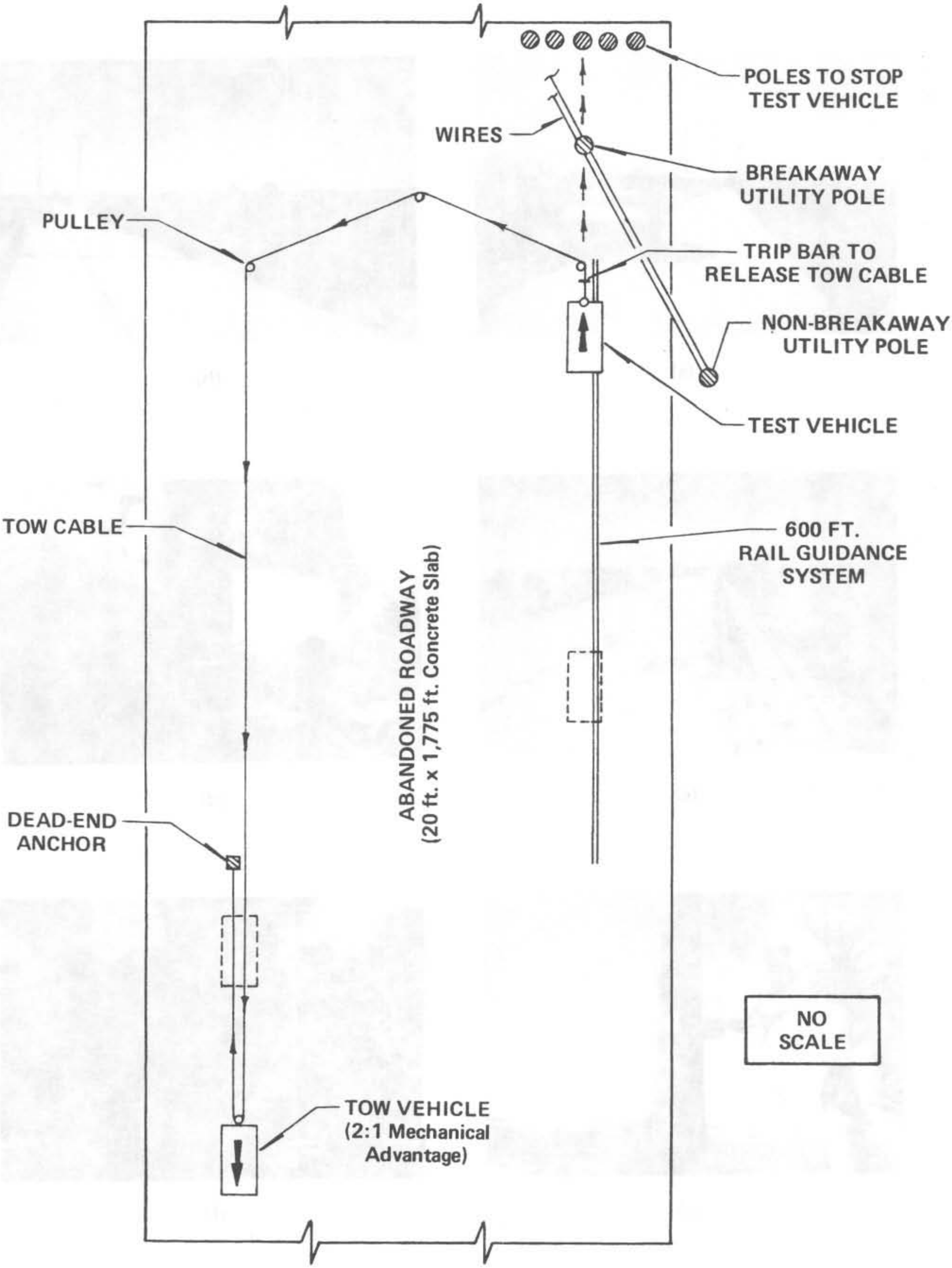
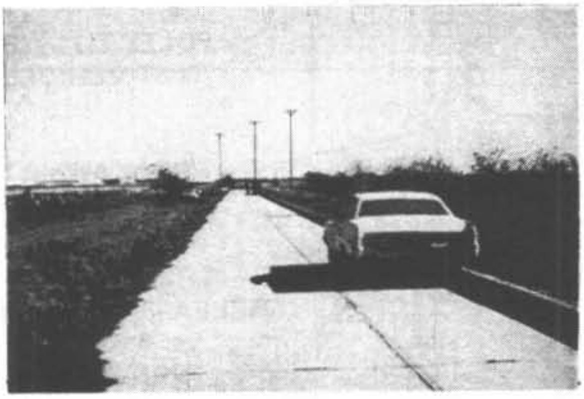


FIGURE 12. REVERSE VEHICLE TOW AND RAIL GUIDANCE SYSTEM

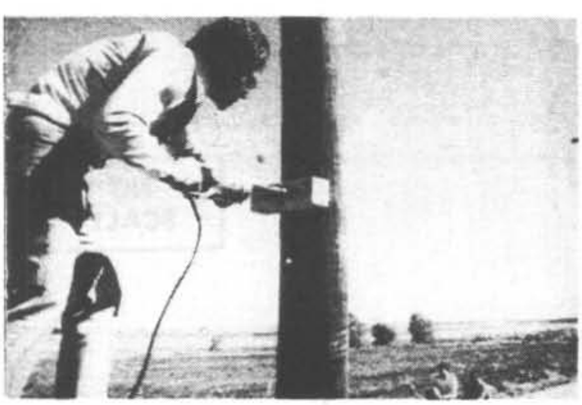


(a)

(b)

(c)

(d)



(e)

(f)

FIGURE 13. PHOTOGRAPHS OF FULL-SCALE TEST SITE

Breakaway Joints

The design of the breakaway joints to provide the "minimum" required section modulus to carry the heavy ice and wind loadings was discussed earlier in the section, entitled "DESIGN CRITERIA". As shown in the photographic views in Figure 13, the lower and upper breakaway joints were made by drilling a row of five 1-in. diameter holes. The spaces between the holes were then sawcut. The 4 x 4-in. wood block drilling jig, which was attached to the pole by two lag screws, was used to maintain the correct spacing and alignment of the holes.

The lower breakaway joint was made about 5-in. above ground, whereas the upper breakaway joint was made 7 ft. above ground level in Test No. 1 and 8 ft. above ground in Tests No. 2 and 3. It was decided to slightly increase the height of the upper breakaway joint in Test No. 2 and 3 to reduce the chance that the upper pole section would impact on the roof or trunk of the vehicles. It was apparent that the lighter vehicles and slower initial velocities used in Test No. 2 and 3 would increase the probability of this occuring. In addition, it was found to be beneficial to have a slightly longer lower pole section. This decreased the possibility that the lower section of the pole would rotate into the windshield. It increased the chance the lower section would come to rest across the hood and roof of the test vehicles. Retrofitting the utility pole to breakaway under vehicle impact by the drilling of 1-in. diameter holes was demonstrated to be a very

High-Speed Film Analysis

Two high-speed camera, described in Table 12, were used in this study. Both cameras were located perpendicular to the path of the test vehicle and at a distance of 100 ft. from the breakaway pole. The film was analyzed by a Vanguard Motion Analyzer, described in Table 12.

TABLE 12

PHOTOGRAPHIC ANALYSIS EQUIPMENT USED

Equipment Description	Pendulum Tests	Full-Scale Test
1. LoCam model 50-003 high speed Camera. Film rate is variable to 500 fm./sec. Actual film speed = 480 fm./sec.	X	X
2. Eastman Kodak high speed Camera, type III. Film rate is variable to 3000 fm./sec. Actual film speed = 900 fm./sec.		X
3. Vanguard Motion Analyzer model C-11P with M16CP projection head. Frame rate is variable to 30 fm./sec. A model 534-C digitizer built at the University of Iowa to input data to a computer is also linked up.	X	X

DISCUSSION OF RESULTS OF FULL-SCALE TEST NO. 1

The first full-scale crash test was conducted with a 4,500 lb standard size automobile at an impact speed of 30 mph. The weight of the test vehicle was in conformance with the "Crash Test Conditions for Breakaway Supports" contained in NCHRP 153 (6); whereas, the impact speed was 10 mph less than that specified in NCHRP 153. This lower selected speed was considered to be more realistic because the accident data compiled in the Lincoln study (see ACCIDENT ANALYSIS Section) showed that only 15 percent of the utility pole accidents occurred at speeds of 40 mph and higher.

Graphs of the change in vehicle velocity and vehicle decelerations obtained from the high-speed film analyses during impact with the breakaway utility pole are shown in Figures 14 and 15, respectively. The complete data analyses of the high-speed film is presented in Appendix D. Referring to Figure 14, the impact velocity was about 31 mph, whereas, the final velocity after the upper breakaway joint failed was about 26 mph. As can be noted in Figure 15, the vehicle decelerations build up to a peak of about 17 G's and then drop-off rapidly after the lower breakaway joint failed. The average vehicle deceleration over a time duration of 50 msec was 5.6 G's. Based on this average level of deceleration, the predicted probability of an injury type accident occurring would be 32 percent. The method to calculate injury probabilities are presented later.

Sequence photographs of the high-speed film at intervals of 20 msec are shown in Figure 16. The stub portion of the pole between the breakaway

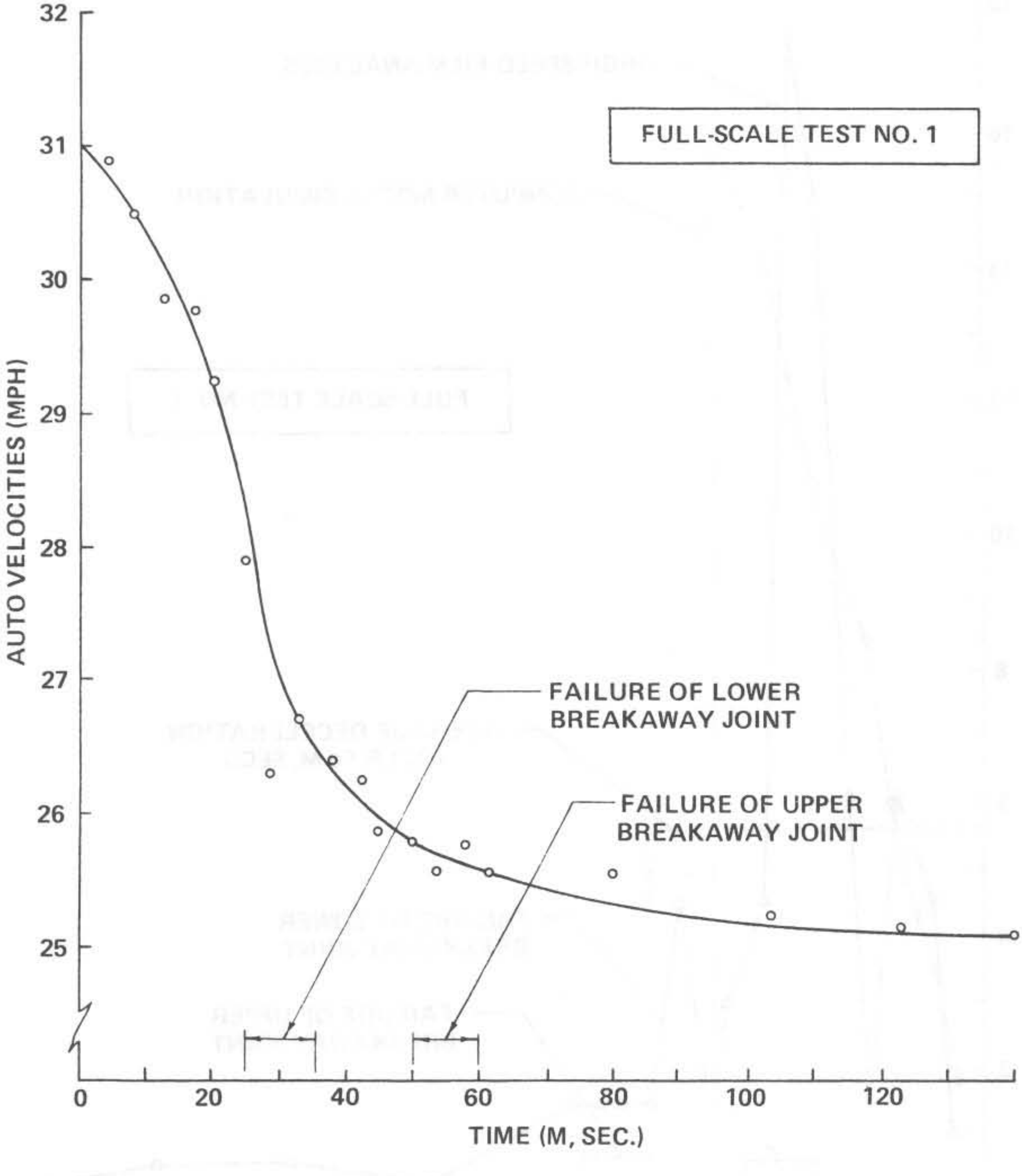


FIGURE 14. SPEED REDUCTION OF VEHICLE DURING IMPACT WITH BREAKAWAY UTILITY POLE

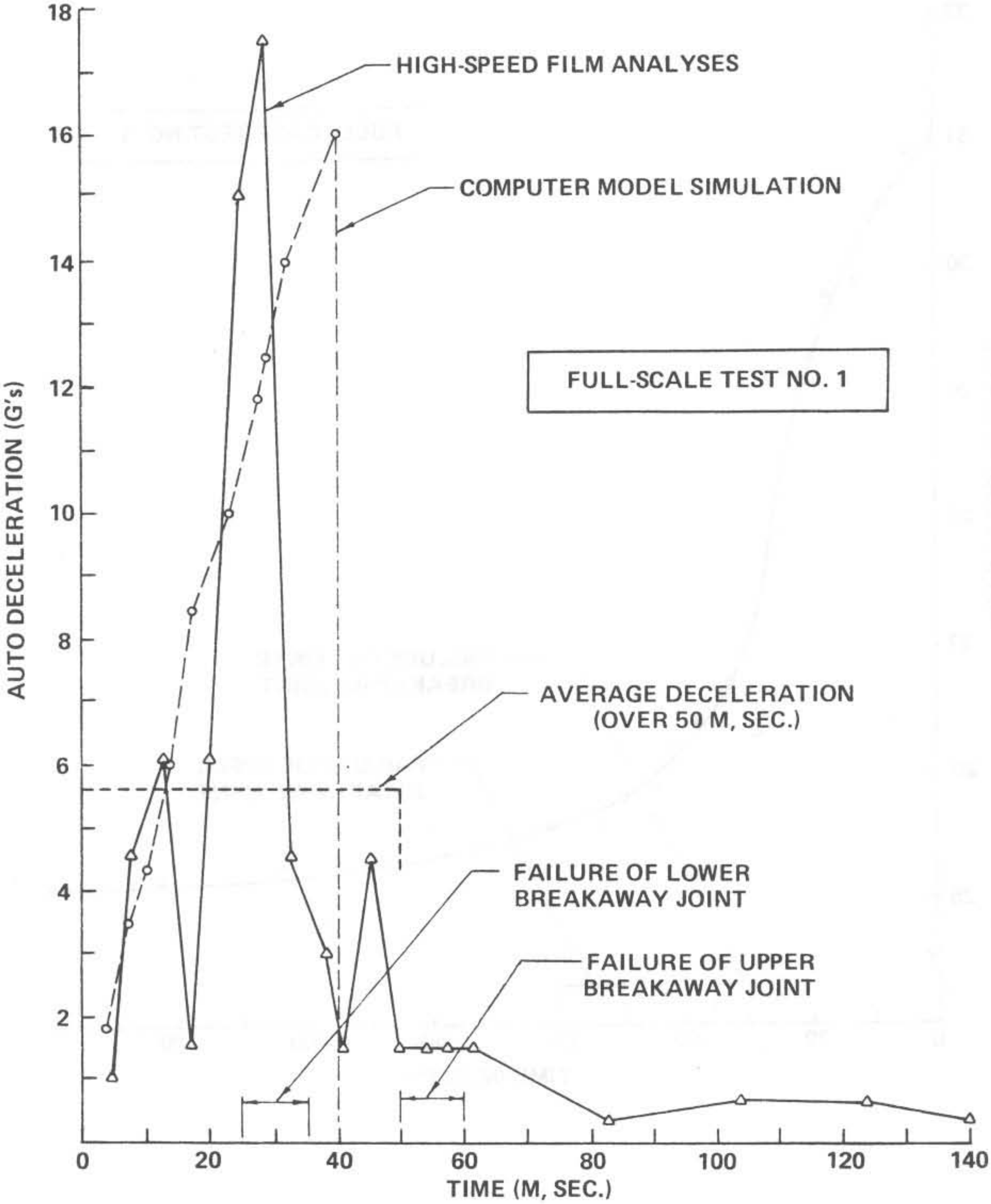
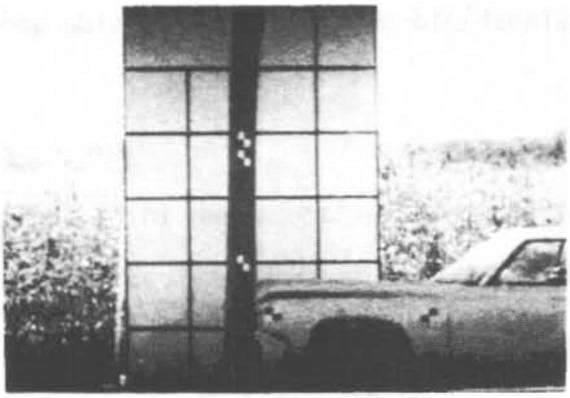
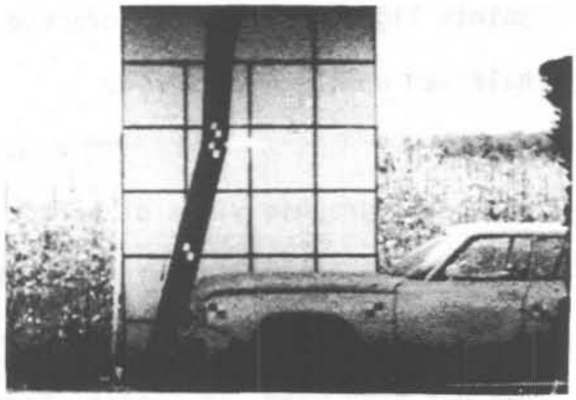


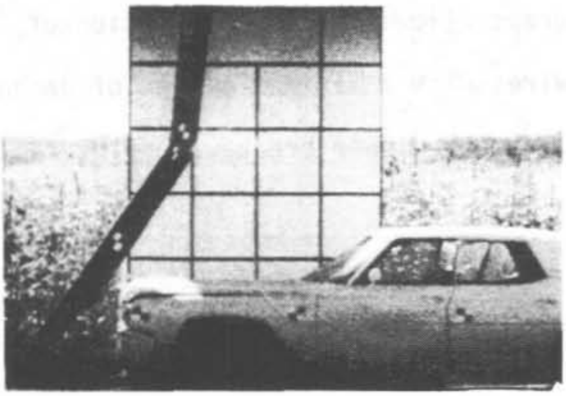
FIGURE 15. VEHICLE C.G. DECELERATIONS: COMPARISON OF HIGH-SPEED FILM ANALYSES AND COMPUTER MODEL



I + 0.02 Sec.

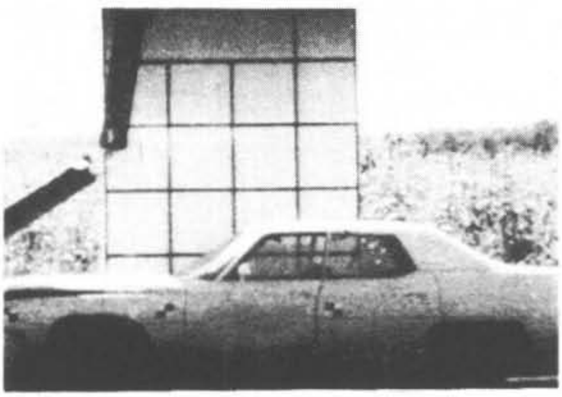


I + 0.04 Sec.

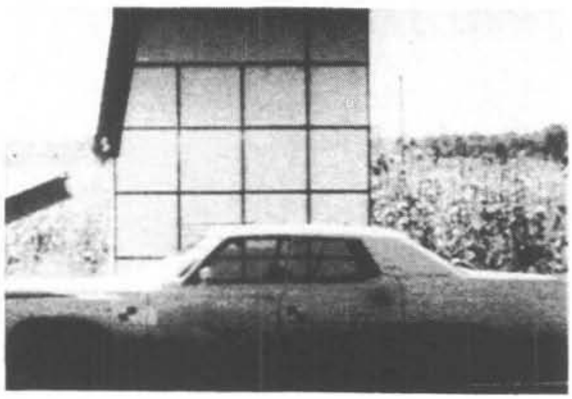


I + 0.06 Sec.

I + 0.08 Sec.



I + 0.10 Sec.



I + 0.12 Sec.

FIGURE 16. HIGH-SPEED FILM OF FULL-SCALE TEST NO. 1

joints lightly struck and cracked the windshield on the passenger side about half way up the windshield.

Photographic views of before and after the test are shown in Figure 17. A backstop, consisting of a row of poles, was used to stop the vehicle after it had traveled 50 ft. beyond the breakaway pole. If the backstop had not been used, it appears from the high-speed film that the portion of the pole above the upper breakaway joint would not have landed on the top passenger side of the vehicle as shown in Figure 17 (photographs b, c, and d). The breakaway flat aluminum wire wraps allowed the upper portion of the pole to separate cleanly from the wires with a minimum amount of damage. The last photograph in Figure 17 shows that the lower breakaway joint failed in a combination of shear and bending.

(a)

(b)

(c)

(d)

(e)

(f)

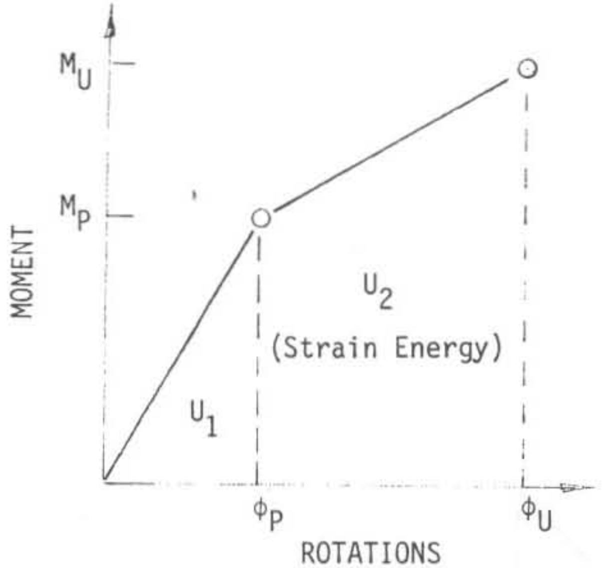
FIGURE 17. PHOTOGRAPHS OF FULL-SCALE TEST NO. 1

Validation of Computer Model

The nonlinear moment-rotation relationship shown in Figure 6 during the development of the model was idealized as a linear relationship shown in Figure 18. This idealization was based on data presented in the Wood Handbook (7), whereby, it was assumed that the strain energy per unit volume in a wood member at the proportional limit was equal to about 20% of the strain energy per unit volume of failure.

In the validation process, it was found that the magnitude of the shearing forces of the lower breakaway joint had a significant influence on the interaction between the vehicle and the utility pole. The nonlinear shear-displacement relationship shown in Figure 6 was idealized as a linear relationship shown in Figure 19.

The vehicle decelerations at its center-of-gravity were used to validate the computer model. The best correlation obtained between the high-speed film analyses and the model is shown in Figure 15. This correlation was based on an ultimate shearing strength of 2,000 psi.



σ_p = 8,000 psi
σ_u = 12,000 psi
S = 73.2 in^3 (Lower Joint)
55.8 in^3 (Upper Joint)
Z = 124.0 m^3 (Lower Joint)
94.6 m^3 (Upper Joint)
E = 1.0 x 10^6psi
I = 388.0 in^4 (Lower Joint)
276.2 in^4 (Upper Joint)

Total Strain Energy, U_T

$$U_T = U_1 + U_2 \qquad \text{---Eq. 12a}$$

$$U_1 = \frac{1}{2} M_P\phi_P = \frac{1}{2} M_P(\frac{M_P}{EI}) \qquad \text{---Eq. 12b}$$

$$U_2 = \frac{1}{2} (M_P + M_U)(\phi_U - \phi_P) = \frac{1}{2} (M_P + M_U)(\phi_U - \frac{M_P}{EI}) \qquad \text{---Eq. 12c}$$

$$U_T = \frac{{M_P}^2}{2EI} (\frac{1}{20\%}) = 2.5 \frac{{M_P}^2}{EI} \qquad \text{---Eq. 12d}$$

Solving Eqs 2, 3, and 4, one obtains:

$$\phi_U = \frac{5{M_P}^2 + M_U M_P}{(M_U + M_P)EI} \qquad \text{---Eq. 12e}$$

Moments

$$M_P = \sigma_P S \qquad \text{---Eq. 13a}$$

$$M_U = \sigma_U Z \qquad \text{---Eq. 13b}$$

FIGURE 18.

MOMENT-ROTATION RELATIONSHIPS OF

BREAKAWAY UTILITY POLE JOINTS

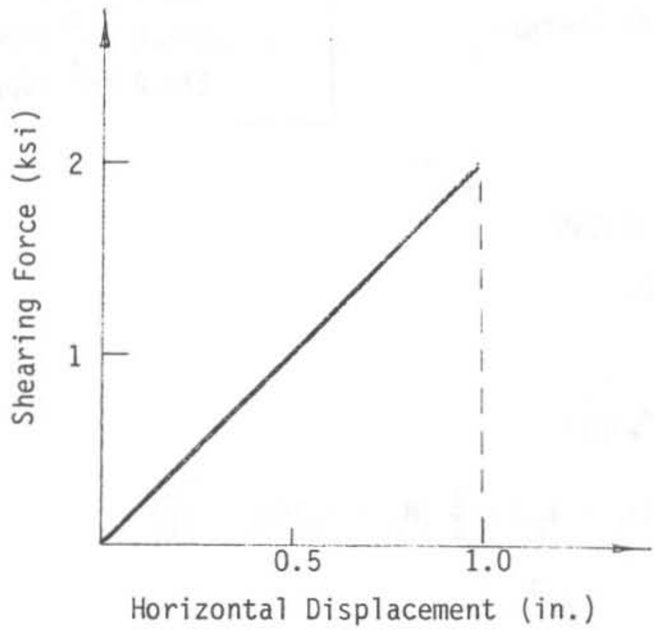


FIGURE 19
SHEAR-DISPLACEMENT RELATIONSHIP
OF BREAKAWAY UTILITY POLE JOINTS

MODEL PARAMETER STUDY

Model parameter studies were conducted to determine the severity of a vehicle colliding with breakaway and non-breakaway utility poles. Two size vehicles (2,250 and 4,500 lbs) and six impact speeds (10, 15, 20, 25, 30 and 35 mph) were investigated. The impact severities computed were used to determine (a) the cost-effectiveness of retrofitting utility poles to break away under impact, and (b) the height of the upper breakaway joint to be used in the second full-scale test. Also, the parameter studies were conducted to gain insight into the performance of breakaway utility poles under various conditions of impact.

Vehicle Front-End Stiffness

The front-end crushing stiffness (k) of a standard size vehicle (4,500 lbs) was based on the work done on breakaway sign supports by Martinez and Post (5) of the Texas Transportation Institute. The equation used in this study is given below.

$$k = 10.0\ W$$
$$= 45{,}000 \text{ lb/ft} \ldots \text{ for } 4{,}500 \text{ lb. vehicle} \qquad \text{---Eq. 14}$$

The front-end crushing stiffness of a subcompact size vehicle (2,250 lbs) was based on the work done on breakaway slot/shim utility poles by Labra (1) of the Southwest Research Institute. In that study, the stiffness of the subcompact vehicle was about 83% of the stiffness of the standard vehicle. The equation used in this study is given below.

$$k = 16.6\ W$$
$$= 37{,}400 \text{ lb/ft} \ldots \text{ for } 2{,}250 \text{ lb. vehicle} \qquad \text{---Eq. 15}$$

Non-Breakaway Utility Poles

The single degree-of-freedom model developed by Emory (10) of a vehicle colliding with a rigid obstacle was used to compute the severity of a vehicle colliding with a non-breakaway utility pole. Development of the model is presented in Appendix E. The equation used to compute decelerations is given below.

$$G_{peak} = \frac{V_I}{g}\sqrt{\frac{kg}{W}} \qquad \text{---Eq. 16a}$$

and

$$G_{avg.} = \frac{2}{\pi} G_{peak} \qquad \text{---Eq. 16b}$$

where: V_I = Impact Speed (fps)

W = vehicle weight (lbs)

k = vehicle front-end stiffness (lb/ft)

g = acceleration due to gravity (32.2 ft/sec^2)

G_{peak} = peak deceleration (G's)

G_{avg} = average deceleration (G's)

The vehicle decelerations and injury probabilities of a vehicle colliding with a non-breakaway utility pole are shown in Table 13. The injury accident probability was determined from the equation below developed later in this study.

$$P = 40\sqrt{\left[\frac{G_{avg}}{7}\right]^2} \qquad \text{---Eq. 17}$$

where: P = Probability of Injury Accident (%)

TABLE 13

INJURY SEVERITY OF VEHICLE COLLIDING WITH NON-BREAKAWAY UTILITY POLE

Vehicle Weight[a.] W (lbs)	Vehicle Impact Speed V_1 (mph)	Vehicle Decelerations (G's)		Probability of Injury Accident P (%)
		Peak	Avg.	
4,500	10	8.2	5.2	28
	15	12.3	7.8	45
	20	16.4	10.4	59
	25	20.5	13.0	74
	30	24.6	15.6	89
	35	28.7	18.2	100
2,250	10	10.6	6.7	38
	15	15.8	10.1	58
	20	21.1	13.4	77
	25	26.4	16.8	96
	30	31.7	20.1	100
	35	36.9	23.5	100

(a.) Front-End Stiffness, k = 10.0 W; for W = 4,500 lb.

k = 16.6 W; for W = 2,250 lbs.

Breakaway Utility Poles

The computer model program developed and validated earlier in this study was used to compute the vehicle decelerations, vehicle momentum changes, vehicle crushing, and time and type of failure occurring at the lower and upper breakaway joints. These results are shown in Table 14 for a standard size vehicle and in Table 15 for a subcompact size vehicle. The injury probabilities were computed by Equation 17.

Findings of Parameter Study

Referring to Tables 14 and 15 it can be seen that the utility pole stopped the vehicle under the lower impact speeds when the upper breakaway joint was located 7 ft above groundline. In these cases, only the upper breakaway joint failed. Increasing the height of the upper breakaway joint to 8 ft above groundline completely eliminated this problem, and as a result, the impact severities were significantly reduced.

The impact severities computed for non-breakaway and breakaway utility poles (Tables 13, 14, and 15) are illustrated in Figure 20. Based on this graph, the following conclusions are evident:

1. Breakaway utility poles are effective in reducing injury accidents.

2. Standard size vehicle impacts are less severe than subcompact vehicle impacts.

3. A standard size vehicle colliding with a non-breakaway utility pole is equal in severity to a subcompact size vehicle colliding with a breakaway utility pole.

TABLE 14

RESULTS OF COMPUTER MODEL SIMULATIONS

Vehicle Weight = 4,500 lb.

Front-End Stiffness = 45,000 lb/ft

Vehicle Speed (mph)		Change in Vehicle Momentum	Height of Upper B/A Joint	Failure of B/A Joints				Vehicle Decelerations (G's)		Prob. of Injury Accident	Vehicle Crushing
				Lower		Upper					
Impact	Final	(lb-sec)	(ft)	Time (msec)	Failure Type	Time (msec)	Failure Type	Peak	Avg.[1.]	(%)	(in)
10.0	0.0	2,055	7	--	--	20	Shear	9.8	9.1	51	12
15.0	0.0	3,080	7	--	--	18	Shear	14.7	13.8	79	18
20.0	12.5	1,540	7	62	Shear	16	Shear	15.2	10.1	58	18[b]
25.0	18.6	1,315	7	46	Shear	15	Shear	14.9	7.1	41	18[b]
30.0	24.0	1,235	7	40	Shear	15	Shear	16.1	7.5	43	19[b]
35.0	29.1	1,210	7	37	Shear	14	Shear	17.7	7.6	44	21[b]
10.0	7.4	535	8	41	Bending	47	Shear	6.7	3.2	19	8[b]
15.0	11.0	820	8	47	Bending	47	Shear	9.7	4.9	28	12[b]
20.0	14.7	1,090	8	51	Bending	47	Shear	13.3	7.3	42	16[b]
25.0	17.8	1,480	8	54	Bending	46	Shear	17.0	10.0	57	20[b]
30.0	21.5	1,740	8	53	Shear	46	Shear	20.2	10.9	62	24[b]
35.0	29.6	1,110	8	37	Shear	38	Bending	17.6	7.6	44	21[b]

a. Averaged over 50 msec

b. Secondary Impact

TABLE 15

RESULTS OF COMPUTER MODEL SIMULATIONS

Vehicle Weight = 2,250 lbs

Front-End Stiffness = 37,400 lb/ft

Vehicle Speed (mph)		Change in Vehicle Momentum	Height of Upper B/A Joint	Failure of B/A Joints				Vehicle Decelerations (G's)		Prob. of Injury Accident	Vehicle Crushing
				Lower		Upper					
Impact	Final	(lb-sec)	(ft)	Time (msec)	Failure Type	Time (msec)	Failure Type	Peak	Avg.[a]	(%)	(in)
10.0	0.0	1,025	7	--	--	20	Shear	13.1	11.0	63	9
15.0	0.0	1,540	7	--	--	18	Shear	19.9	15.5	89	13
20.0	0.0	2.055	7	--	--	17	Shear	26.3	21.6	100	17
25.0	8.3	1,715	7	62	Shear	15	Shear	30.7	19.7	100	20
30.0	13.5	1,695	7	56	Shear	15	Shear	35.3	19.2	100	23
35.0	23.3	1,200	7	41	Bending	14	Shear	33.5	14.9	85	22
10.0	5.4	470	8	48	Bending	48	Shear	11.5	5.5	31	8[b]
15.0	8.3	690	8	47	Bending	47	Shear	16.8	8.1	46	11[b]
20.0	11.4	885	8	47	Bending	46	Shear	22.1	10.9	62	14[b]
25.0	13.6	1,170	8	50	Bending	46	Shear	28.2	13.7	78	18[b]
30.0	15.0	1,540	8	54	Shear	45	Shear	34.0	18.3	100	22[b]
35.0	23.7	1,160	8	40	Shear	41	Shear	33.3	15.0	86	22[b]

a. Averaged over 50 msec

b. Secondary Impact

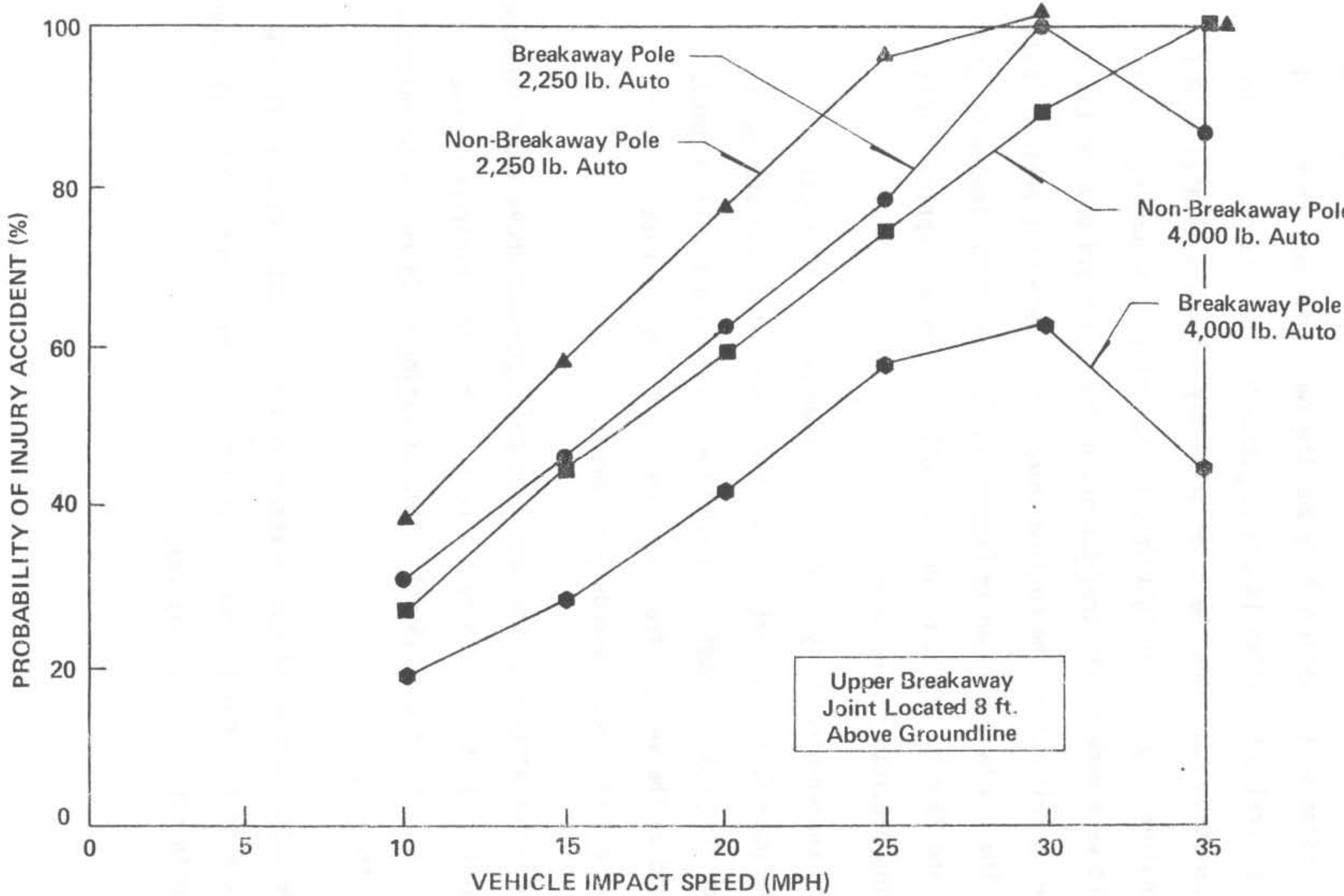


FIGURE 20. SEVERITY OF VEHICLE COLLISIONS WITH BREAKAWAY AND NON-BREAKAWAY UTILITY POLES

No attempt was made in this study to monitor secondary impacts between the upper portion of the vehicle body and the two rigid body portions of the pole. Referring to Tables 14 and 15 , secondary impacts occurred in all the simulation runs when the upper breakaway joint was located at 8 ft above groundline. To gain insight into the severity of secondary impacts, three graphs were made of the trajectories of the two rigid body portions of the pole in relation to the outline shadow of a subcompact vehicle (1974 Vega GT). The graphs are shown in Figure 21, 22, and 23 for impact speeds of 15, 20, and 25 mph. Based on an examination of these graphical plots, the following predictions are made:

1. The center-of-gravity of the 8 ft "breakaway stub" section of the pole is high enough so that the upper end of the stub will not penetrate through the vehicle windshield, but will instead, land on the vehicle front hood and roof. This situation exists for all the impact speeds considered.

2. The upper portion of the breakaway pole (portion above upper breakaway joint) will strike the back windshield of the vehicle under the low impact speed of 15 mph. This situation could result in injuries in the rear seat.

3. The upper portion of the breakaway pole will most likely strike the trunk of the vehicle under an impact speed of 20 mph. This situation should not result in any injuries.

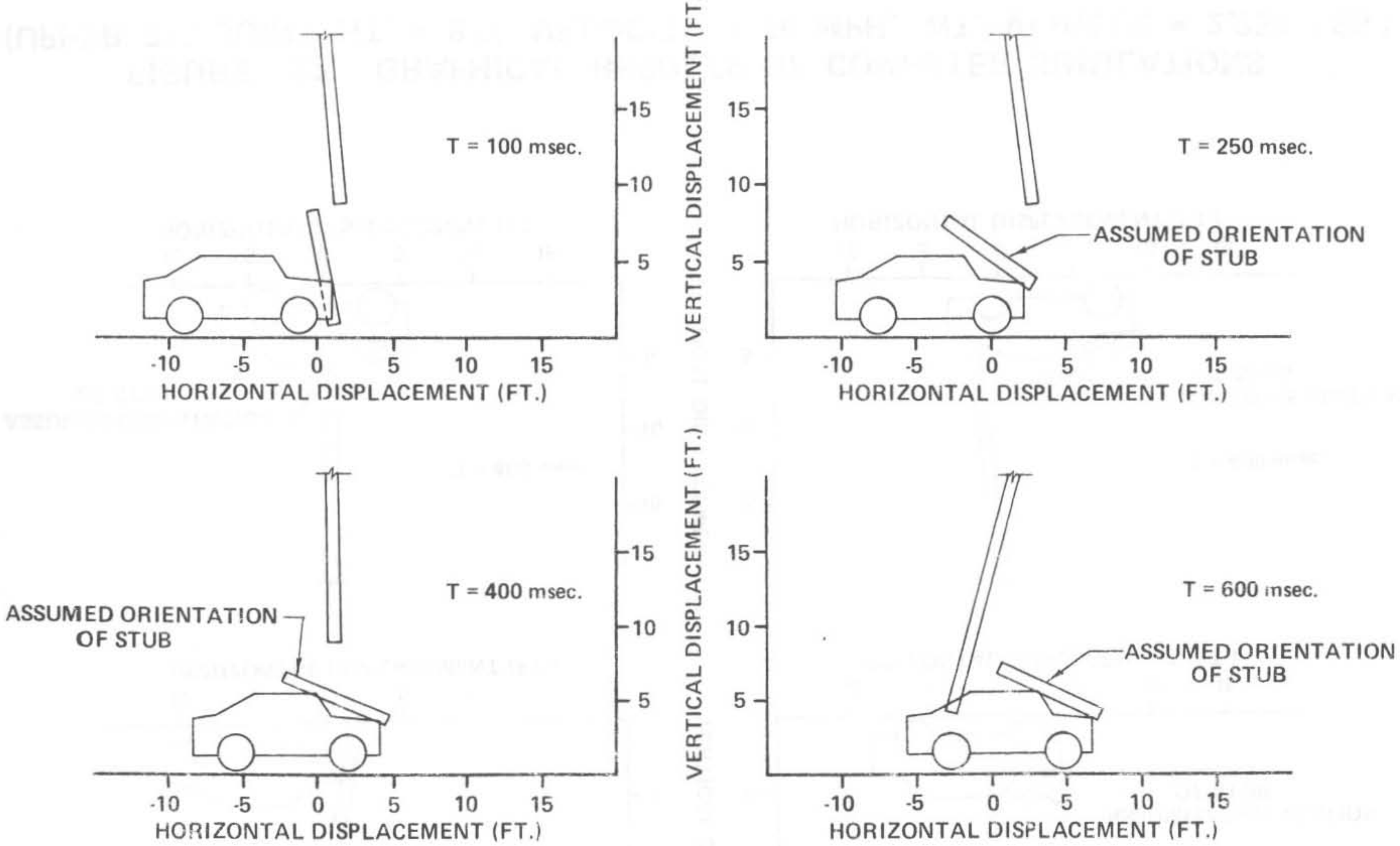


FIGURE 21. GRAPHICAL RESULTS OF COMPUTER SIMULATIONS
(UPPER B/A JOINT HT. = 8.0', VELOCITY = 15 MPH, WT. VEHICLE = 2,250 LBS.)

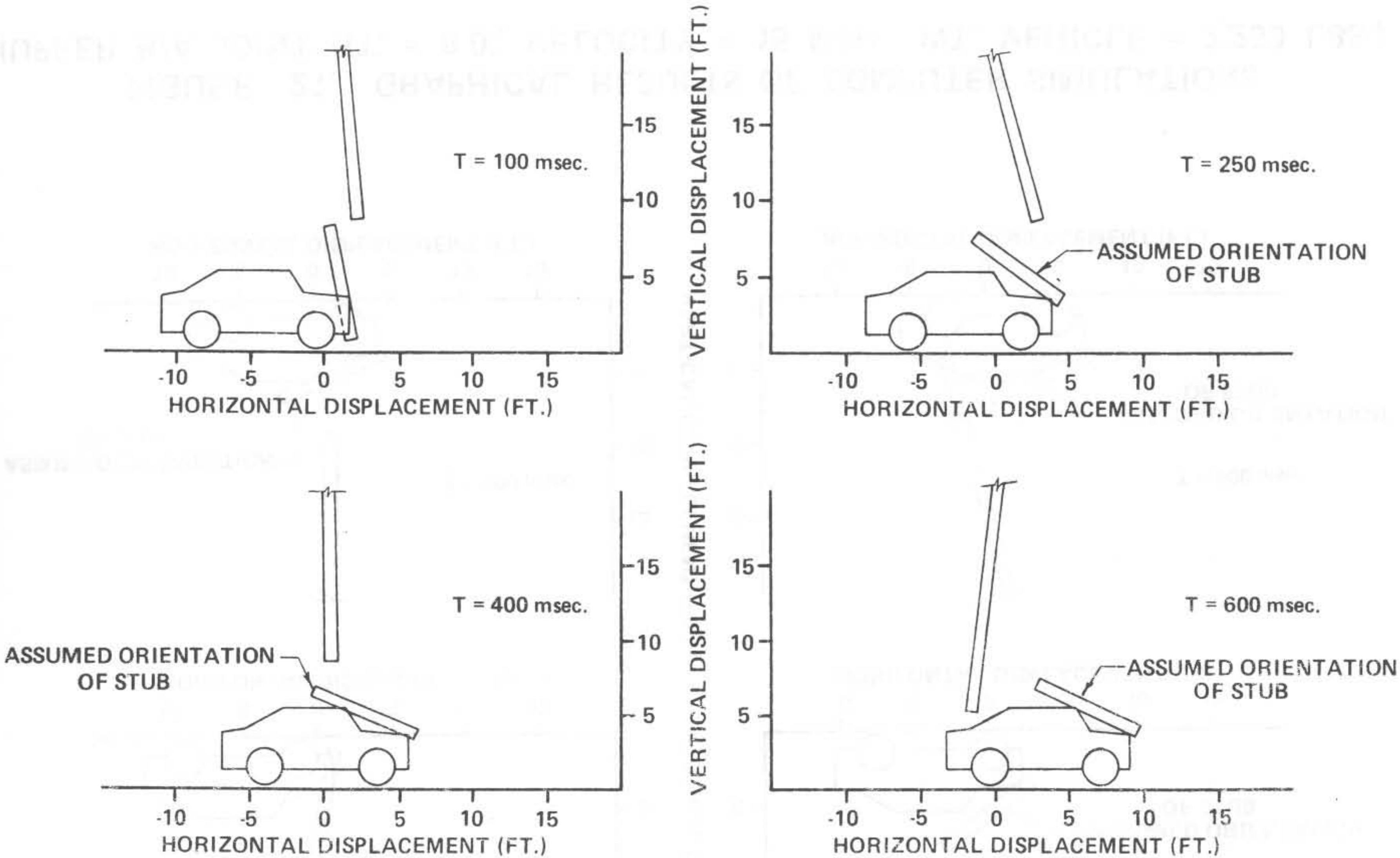


FIGURE 22. GRAPHICAL RESULTS OF COMPUTER SIMULATIONS
(UPPER B/A JOINT HT. = 8.0', VELOCITY = 20 MPH, WT. VEHICLE = 2,250 LBS.)

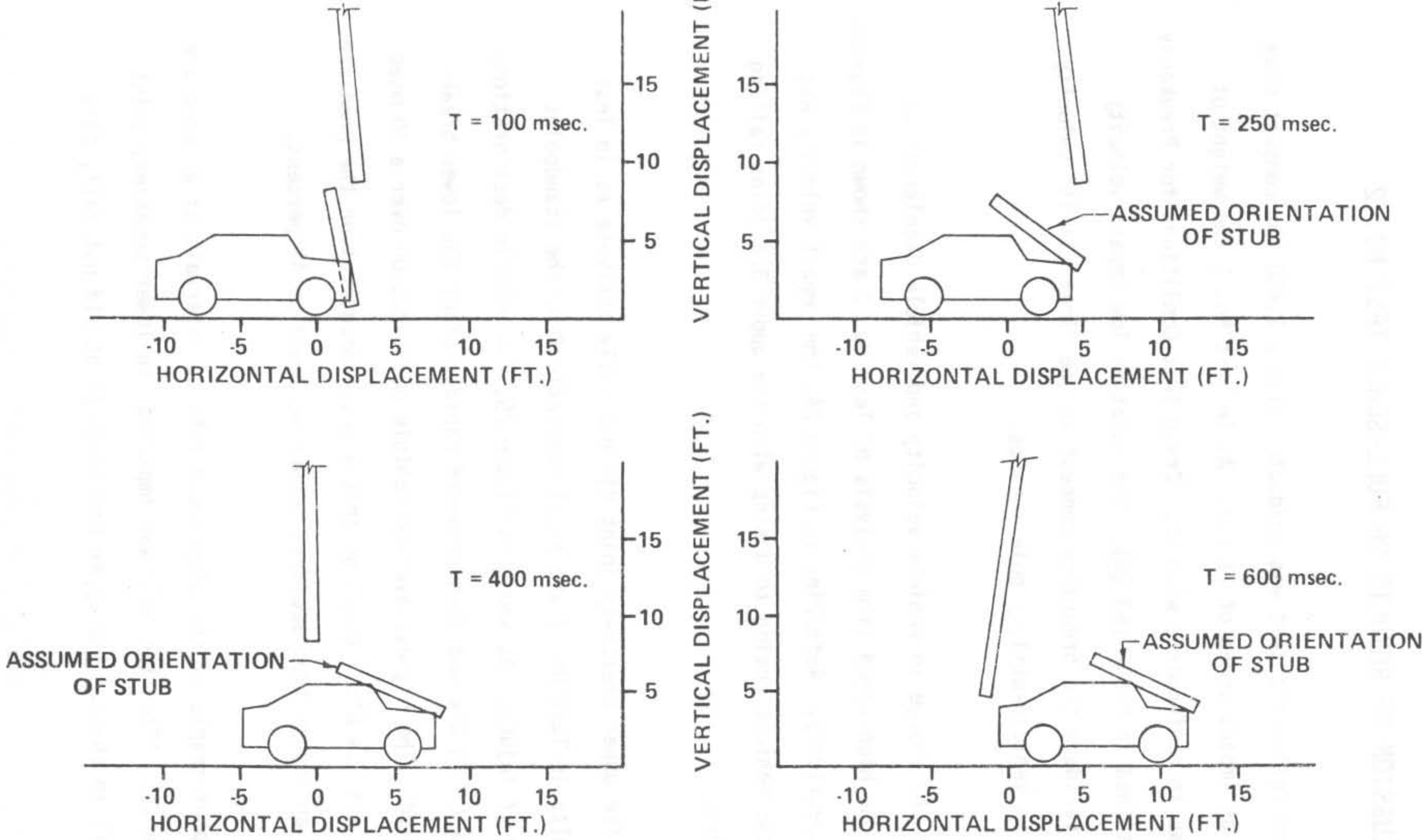


FIGURE 23. GRAPHICAL RESULTS OF COMPUTER SIMULATIONS
(UPPER B/A JOINT HT. = 8.0′, VELOCITY = 25 MPH, WT. VEHICLE = 2,250 LBS.)

DISCUSSION OF RESULTS OF FULL-SCALE TEST NO. 2

The second full-scale test was conducted with a 2,450 lb. compact size automobile at an impact speed of 21 mph. As in Test No. 1 the weight of the vehicle was in conformance with the "Crash Test Conditions for Breakaway Supports" contained in NCHRP 153 (6). The relative low impact velocity was chosen to validate the breakaway concept at the "lower limit" velocity corresponding to vehicle-utility pole impacts.

Graphs of the change in vehicle velocity and vehicle decelerations obtained from the high-speed film analysis of Test No. 2 are shown in Figures 24 and 25, respectively. Referring to Figure 24, the impact velocity was 21 mph, with the vehicle coming to a stop with the upper B/A joint failing to fully activate.

Although the upper breakaway joint did not fully activate as in Test No. 1 the results in Test No. 2 are still favorable from the standpoint of probability of injury. As shown in Figure 25, the vehicle decelerations build to a peak of 23 G's and then drop-off rapidly after the lower breakaway joint failed. The highest average vehicle deceleration over a 50 msec time increment was 7.4 G's. Based on this average deceleration the predicted probability of an injury type accident occurring would be 42 percent.

Sequence photographs of the high-speed film at intervals of 20 msec are shown in Figure 26. After the pole was impacted the lower breakaway joint appeared to fail in shear. The upper breakaway joint did not fail, this

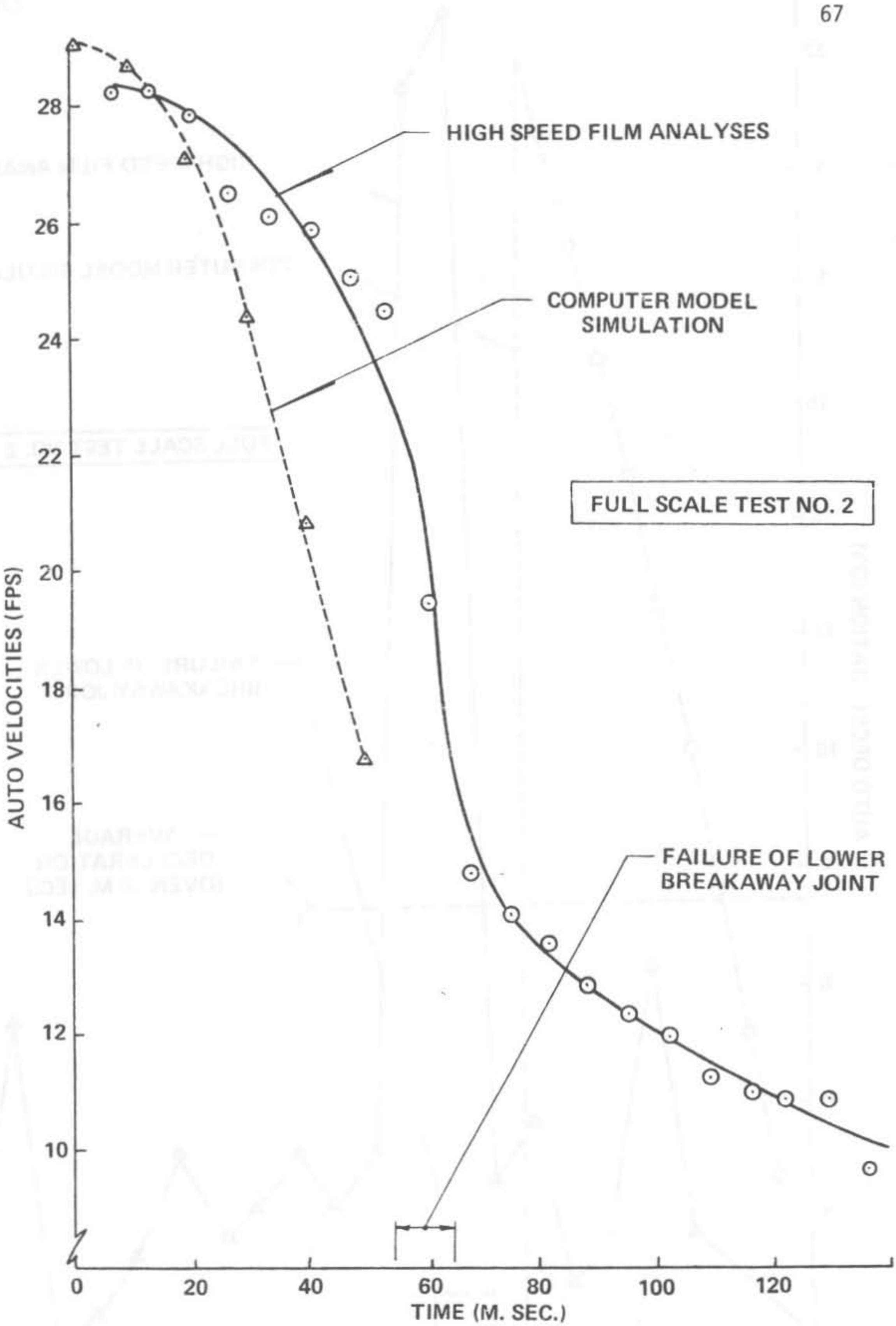


FIGURE 24. SPEED REDUCTION OF VEHICLE DURING IMPACT WITH BREAKAWAY UTILITY POLE

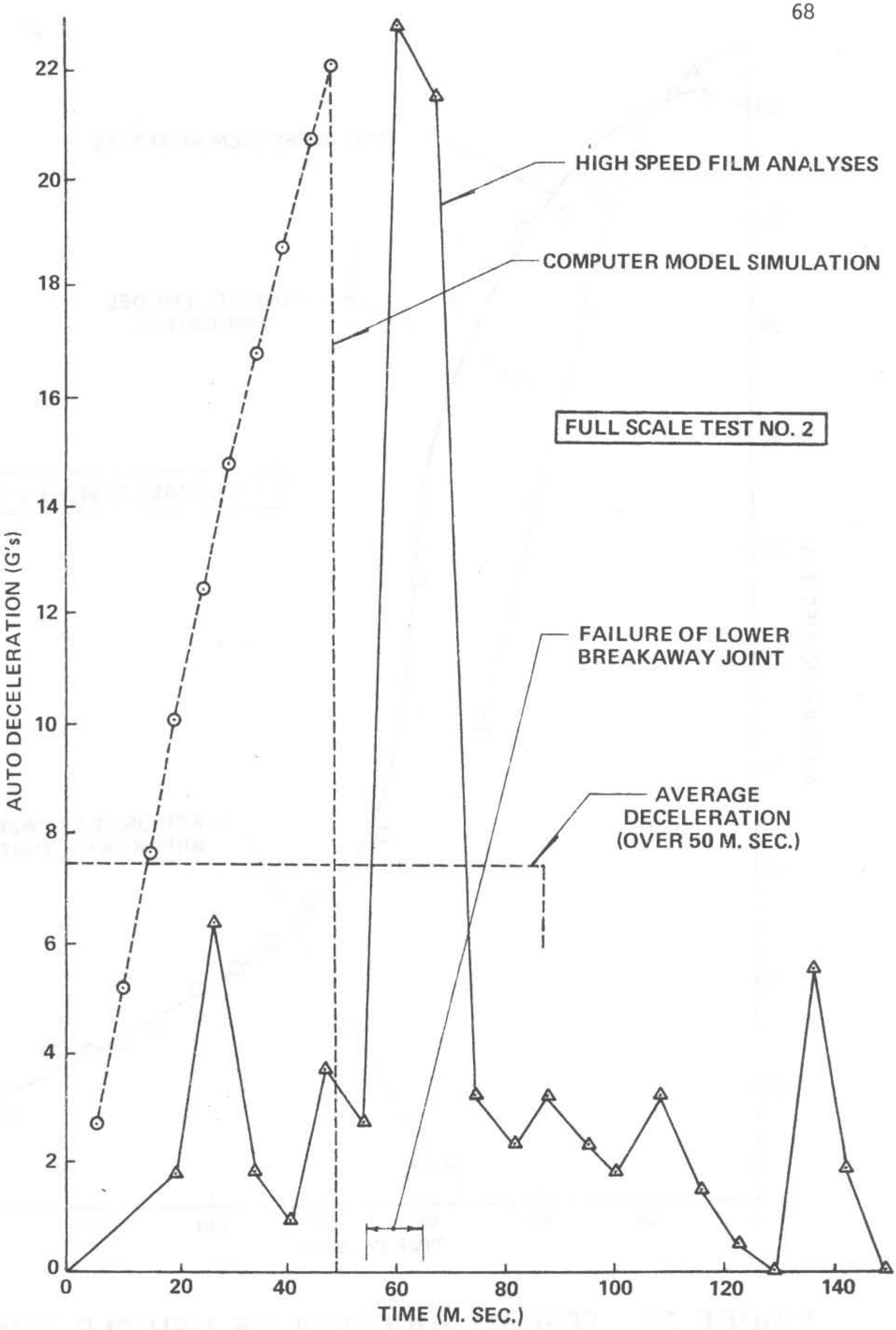


FIGURE 25. VEHICLE C.G. DECELERATIONS: COMPARISON OF HIGH-SPEED FILM ANALYSES AND COMPUTER MODEL

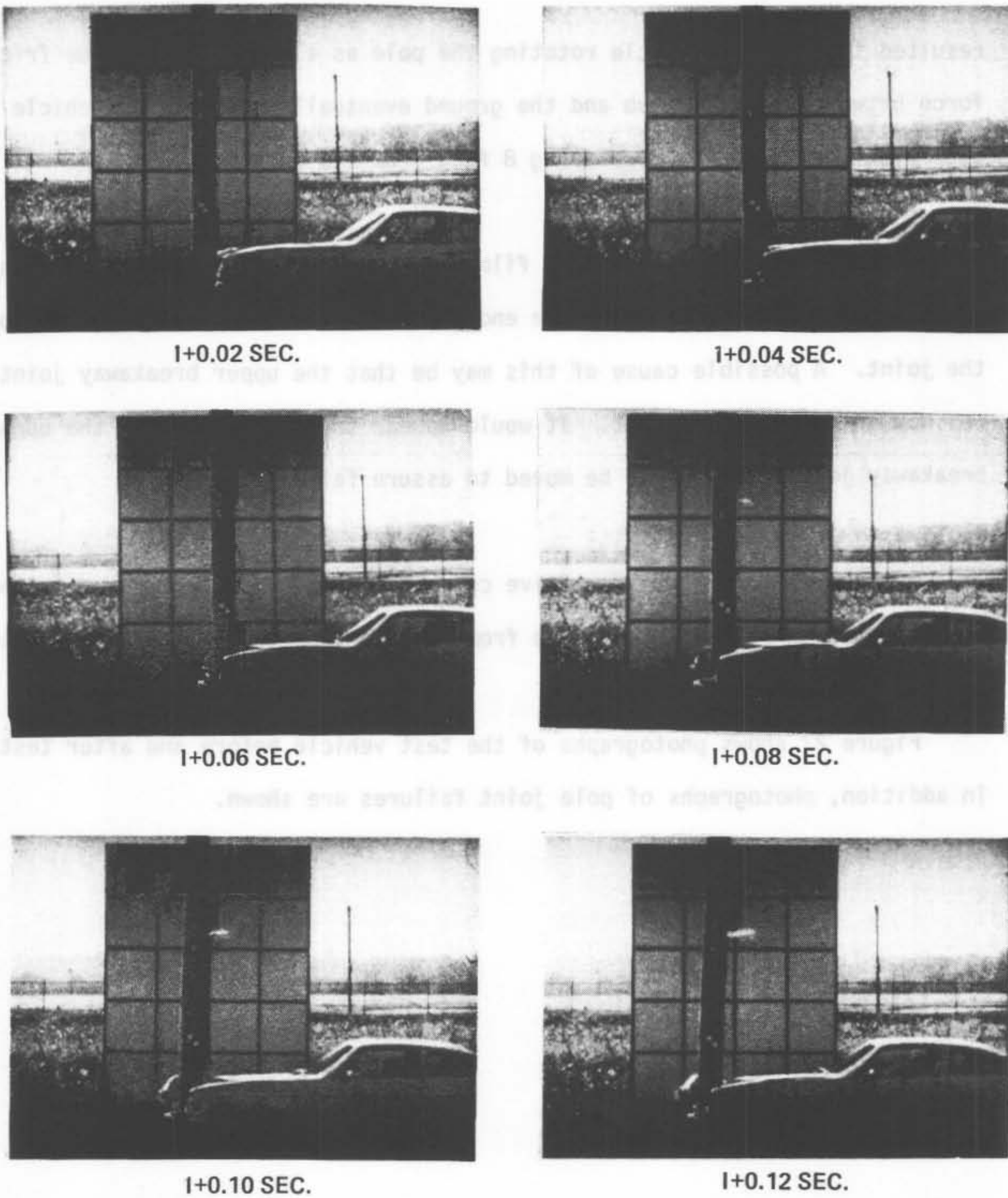


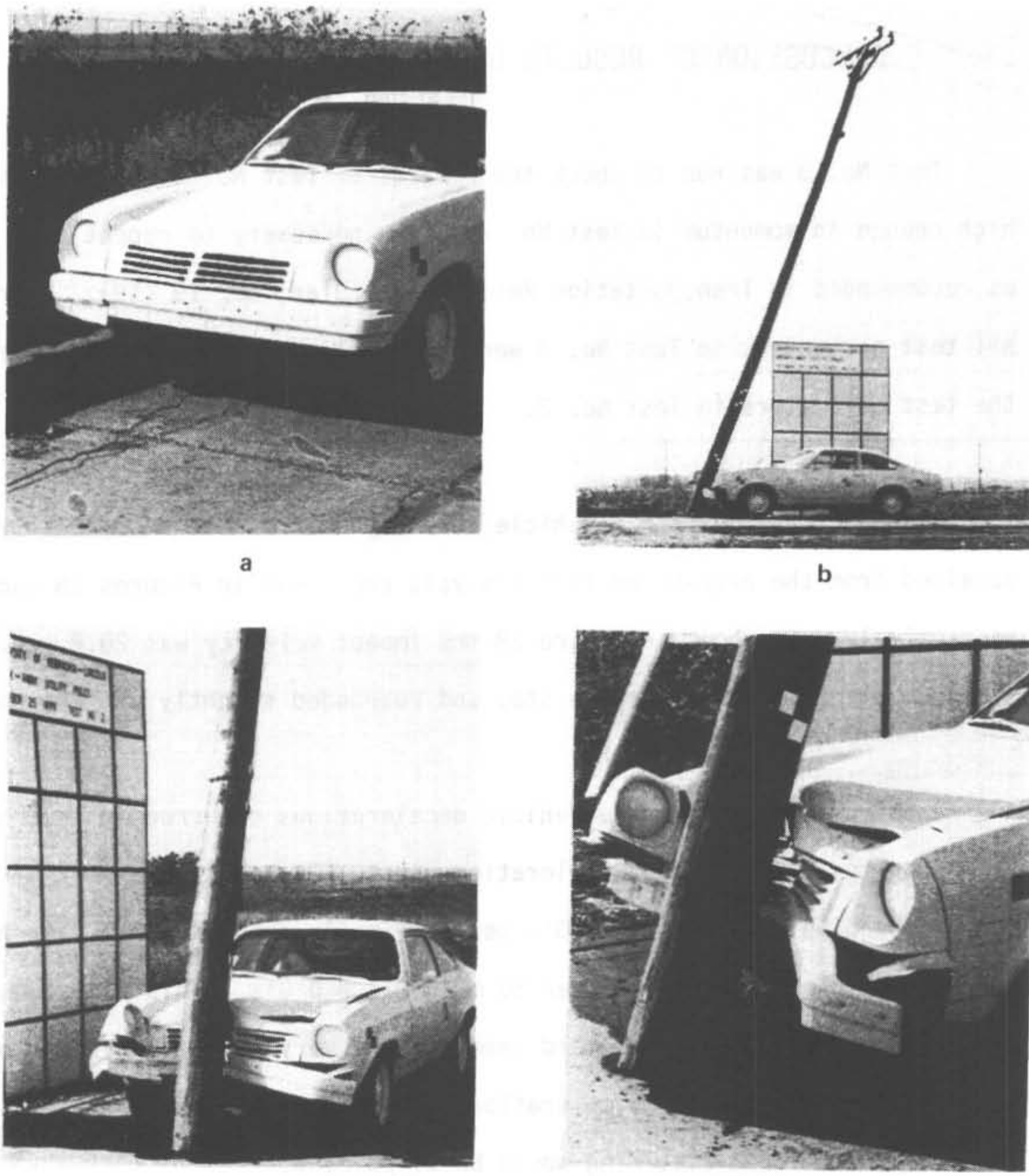
FIGURE 26.
HIGH-SPEED FILM OF FULL-SCALE TEST NO. 2

resulted in the test vehicle rotating the pole as a single unit. The frictional force between the pole stub and the ground eventually brought the vehicle to a stop with the pole stub displacing 8 feet from its original position.

In evaluating the high-speed film it appeared that the upper breakaway joint was not subjected to a large enough flexural wave to cause failure of the joint. A possible cause of this may be that the upper breakaway joint was not at an optimum height. It would appear that the height of the upper breakaway joint may need to be moved to assure failure.

Due to the use of the "positive connections" the pole did not release from the wires. This is favorable from the standpoint of repair and replacement.

Figure 27 shows photographs of the test vehicle before and after testing. In addition, photographs of pole joint failures are shown.



a b c d

FIGURE 27.
PHOTOGRAPHS OF FULL-SCALE TEST NO. 2

DISCUSSION OF RESULTS OF FULL-SCALE TEST NO. 3

Test No. 3 was run to check the results of Test No. 2. Due to the high change in momentum in Test No. 2 it was necessary to repeat this test as recommended in Transportation Research Circular, No. 19 (19). Therefore all test parameters in Test No. 3 were as nearly identical as possible to the test parameters in Test No. 2.

Graphs of the change in vehicle velocity and vehicle decelerations obtained from the high-speed film analysis are shown in Figures 28 and 29, respectively. As shown in Figure 28 the impact velocity was 20.8 mph. The test vehicle came to a complete stop and rebounded slightly off the pole.

A definite change in the vehicle decelerations occurred in Test No. 3. Referring to Figure 29 the decelerations initially build to a peak of 15 G's, drop off and build again to 20 G's before finally dropping off. The highest average vehicle deceleration over 50 msec was 8.0 G's. This was somewhat surprising considering what would seem to be a very "stiff" barrier condition. Based on average level of deceleration, the predicted probability of an injury type accident occurring would be 51 percent.

Sequence photographs of the high-speed film at intervals of 20 msec. are shown in Figure 30.

The soil yielded around the pole causing the lower part of the pole to rotate forward and partially fail the upper breakaway joint. Although the

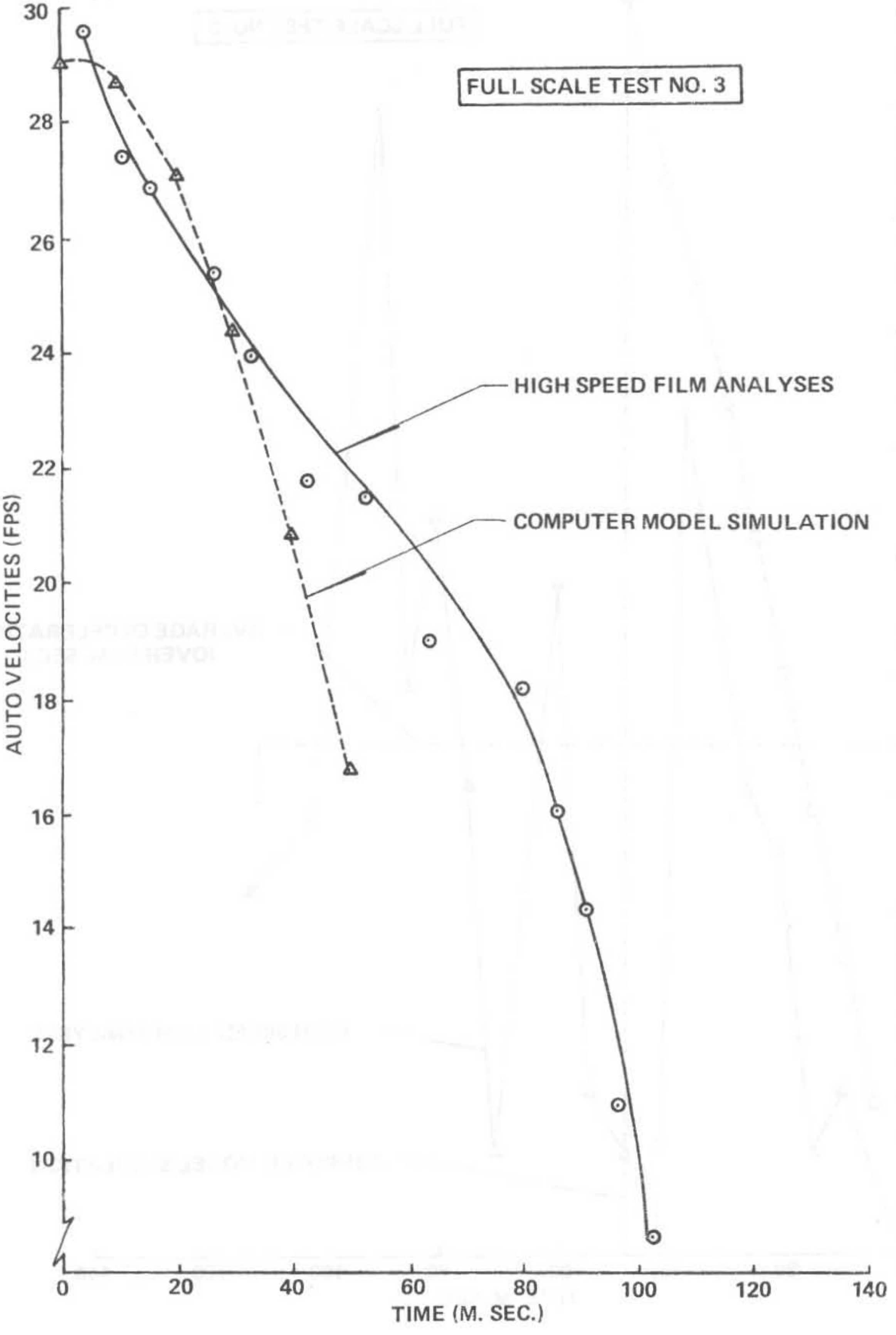


FIGURE 28. SPEED REDUCTION OF VEHICLE DURING IMPACT WITH BREAKAWAY UTILITY POLE

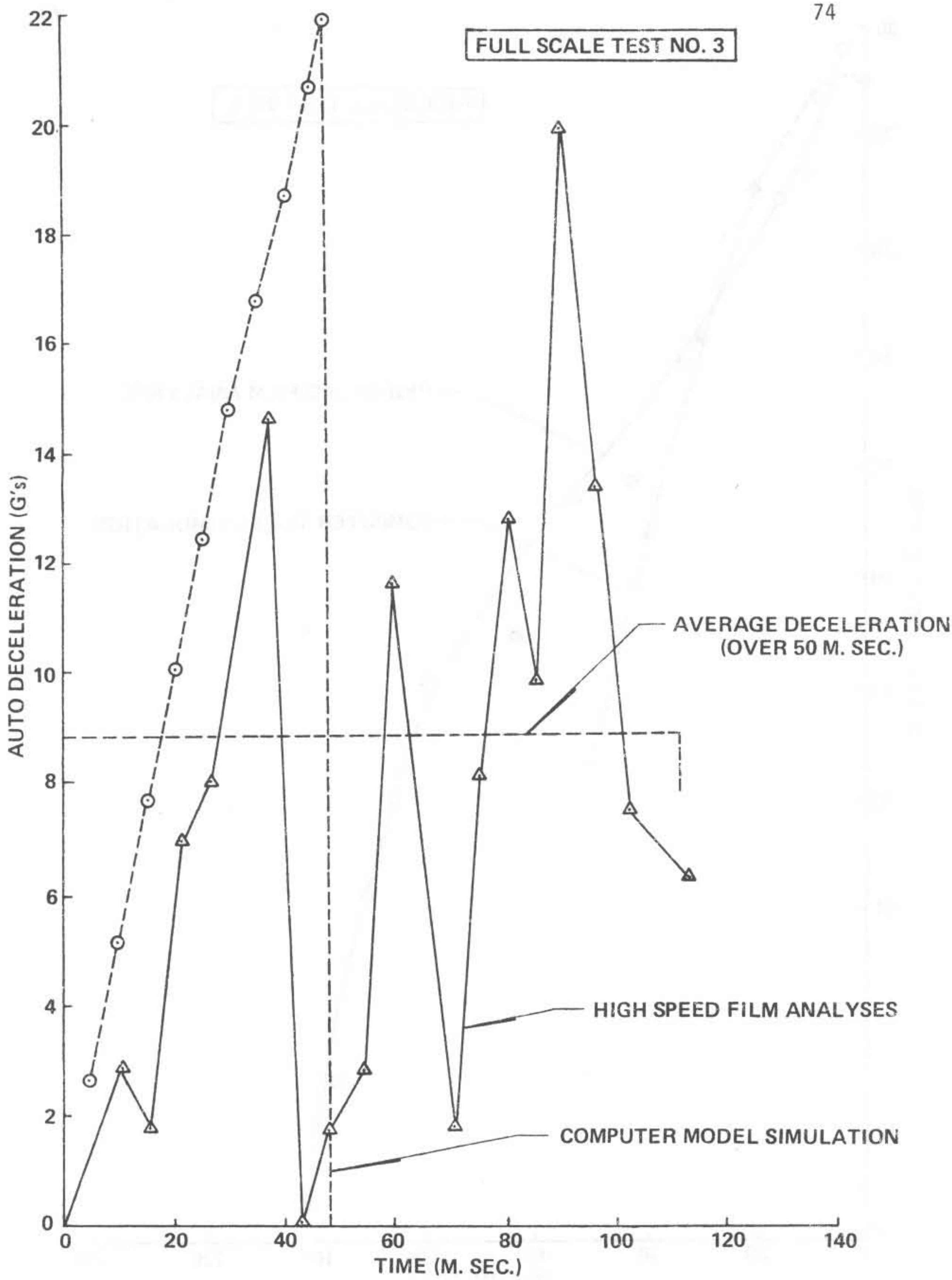
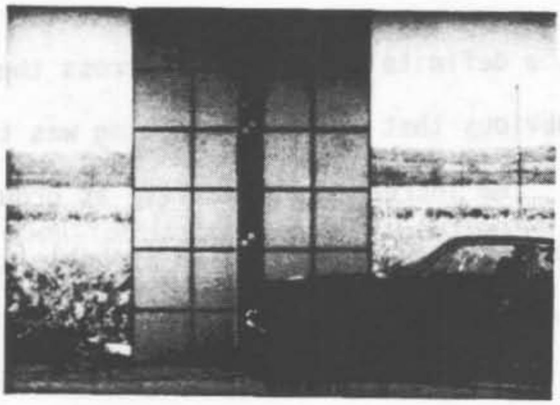
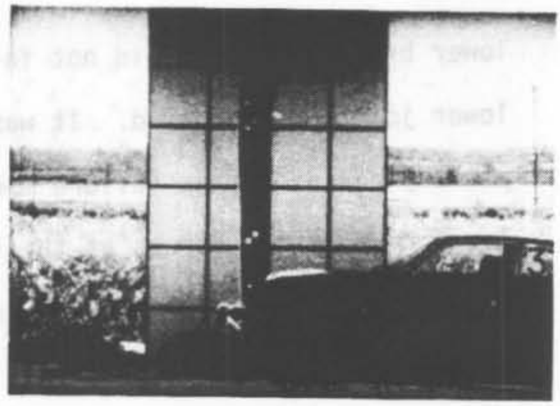


FIGURE 29. VEHICLE C.G. DECELERATION: COMPARISON OF HIGH-SPEED FILM ANALYSIS AND COMPUTER MODEL



I+0.04 SEC.



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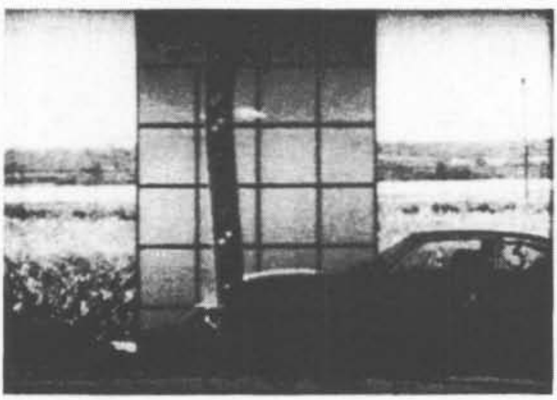
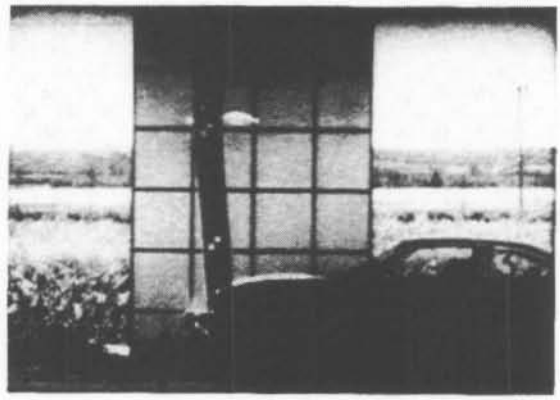
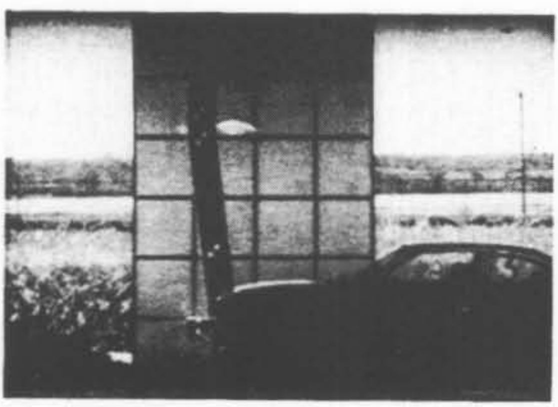


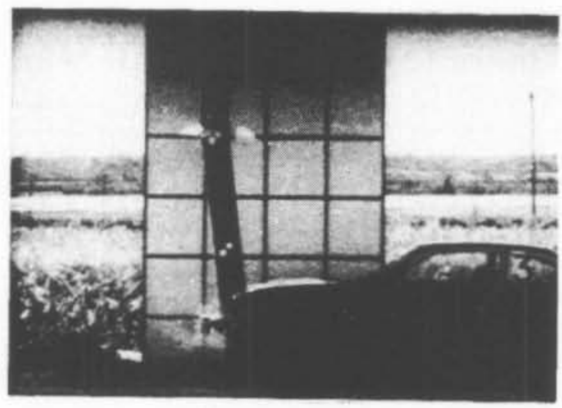
I+0.12 SEC.



I+0.16 SEC.



I+0.20 SEC.



I+0.24 SEC.

FIGURE 30.
HIGH-SPEED FILM OF FULL-SCALE TEST NO. 3

lower breakaway joint did not fail, a definite displacement across the lower joint had occurred. It was obvious that the soil yielding was the primary cause of this failure mode. The increased flexibility at ground level reduced the stress at the lower breakaway joint. The probable cause of the soil yielding was high moisture content.

Figure 31 shows photographs of the test vehicle before and after testing. In addition photographs of the pole joint failures are shown.

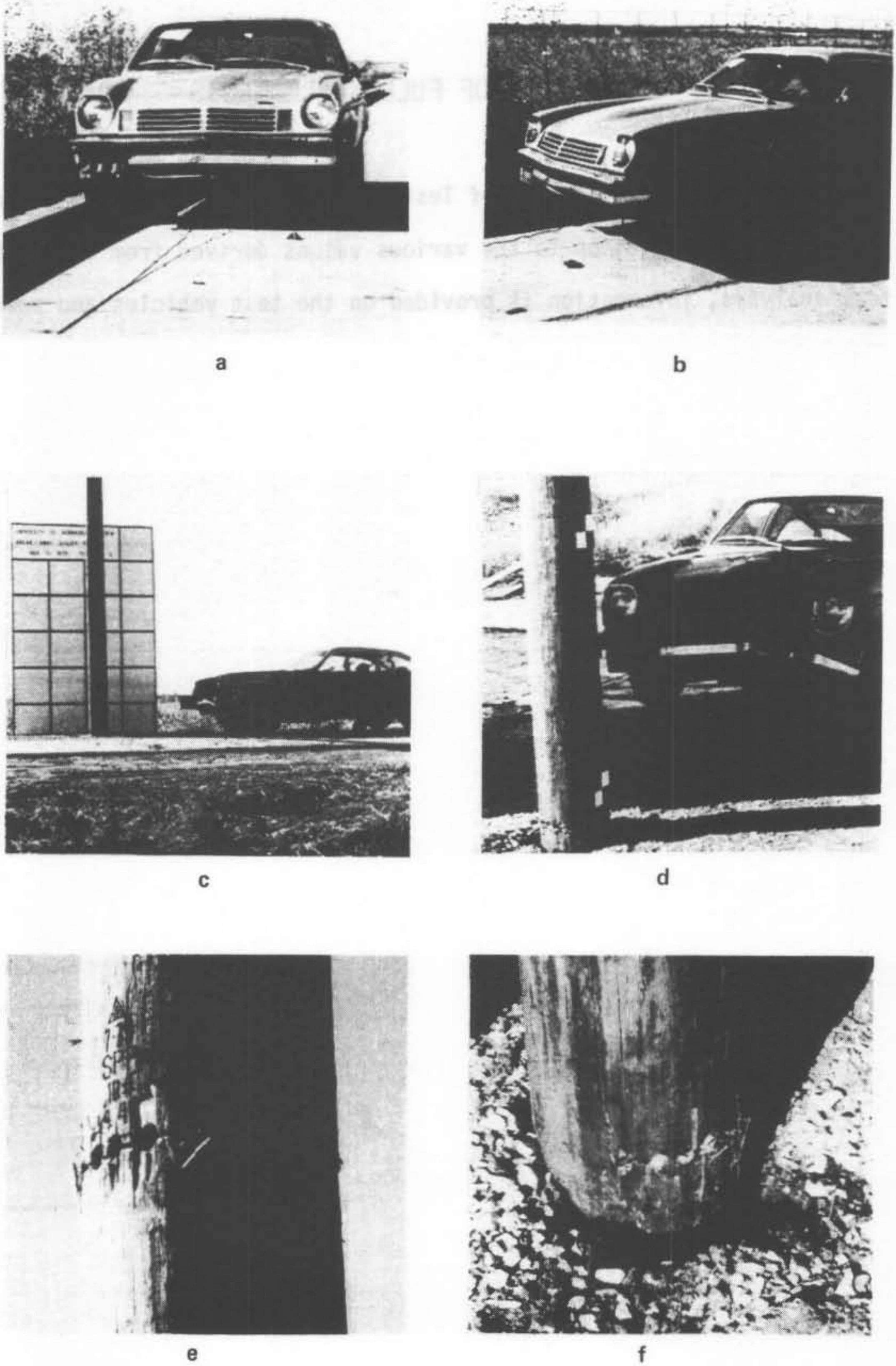


FIGURE 31.
PHOTOGRAPHS OF FULL-SCALE TEST NO. 3

RESULTS OF FULL-SCALE TESTS

A summary of the results of Tests No. 1, 2 and 3 is shown in Tables 16, 17, and 18. In addition to the various values derived from the high-speed film analysis, information is provided on the test vehicles and poles.

TABLE 16 DESCRIPTION OF TEST VEHICLES AND POLES USED IN FULL-SCALE TESTS

Vehicle and Pole Parameters	Test 1	Test 2	Test 3
Test Vehicle:			
Manufacturer	Buick	Gen. Motors	Gen. Motors
Model	Electra 225	Vega-GT	Vega
Year	1973	1974	1974
Weight (lbs)	4600	2450	2450
Test Pole:			
Type	S.Y. Pine	S.Y. Pine	S.Y. Pine
Class	4	4	4
Length (ft)	40	40	40
Height above ground (ft)	34	34	34
Top wire configuration			
Wire type	336.4 KCM 18/1	336.4 KCM 18/1	336.4 KCM 18/1
Number of wires	2	2	2
Type of crossarms	single	double	double
Connection type	breakaway	positive	positive
Wire height (ft)	33	33	33
Bottom wire configuration			
Wire type	2/0, 6/1	2/0, 6/1	2/0, 6/1
Number of wires	1	1	1
Type of crossarms	none	none	none
Connection type	breakaway	positive	positive
Wire height (ft)	27	27	27
Span between poles (ft)	75-100	75-100	75-100
Upper breakaway joint			
Height above ground (ft)	7.0	8.0	8.0
Section modulas (in^3)	56.0	56.0	56.0
Net area (in^2)	21.0	21.0	21.0
Lower breakaway joint			
Height above ground (ft)	0.50	0.50	0.50
Section modulas (in^3)	74.0	74.0	74.0
Net area (in^2)	25.5	25.5	25.5

TABLE 17 SUMMARY OF FULL-SCALE TEST RESULTS

Full-Scale Test Results	Test 1	Test 2	Test 3
Impact velocity (mph)	30.8	21.4	20.8
Final velocity (mph)	25.1	0	0
Change in velocity (mph)	5.7	21.4	20.8
Momentum Change (lb-sec)	1190	951	1042
Highest Average Deceleration*(G's)	5.6	7.4	8.9
Peak Decelerations (G's)	17	22.8	20.0
Severity Index	0.8	1.1	1.3
Probability of Injury (%)	32	42	51
Failure of breakaway joints			
Upper Joint			
Failure	yes	no	partial
Failure type	bending	--	bending
Lower Joint			
Failure	yes	yes	no
Failure type	shear	shear	--

* Averaged over 50 msec.

TABLE 18 SUMMARY OF VEHICLE DAMAGE ESTIMATES*

Damage Costs	Test 1	Test 2	Test 3
Repair labor	—	$ 445	$ 497
Parts:			
New	—	884	967
Used	—	484	567
Total Repair Costs			
New	—	1329	1467
Used	—	929	1067

* See Appendix F for damage estimates

SEVERITY OF AUTOMOBILE COLLISIONS WITH UTILITY POLES

The severity of an automobile collision with a utility pole was expressed in terms of a Severity-Index. The severity-index is computed as the ratio of the measured or computed resultant automobile acceleration to the resultant "tolerable" automobile acceleration that defines an ellipsoidal surface. This ratio can be expressed mathematically by Eq. 3. An in-depth discussion the development of Eq. 3 was presented by Ross and Post (11) and Weaver (12).

$$SI = \frac{G_{total\ Auto}}{G_{total\ Occupant}} = \sqrt{\left[\frac{G_{long}}{G_{XL}}\right]^2 + \left[\frac{G_{lat}}{G_{YL}}\right]^2 + \left[\frac{G_{vevt}}{G_{ZL}}\right]^2} \quad \text{---Eq. 18}$$

where:

SI = Severity-Index

$G_{total\ Auto}$ = Resultant Auto Acceleration

$G_{total\ Occupant}$ = Resultant Tolerable Acceleration

G_{long} = Auto Acceleration along longitudinal x-axis

G_{lat} = Auto Acceleration along lateral y-axis

G_{vert} = Auto Acceleration along vertical z-axis

G_{XL} = Tolerable Acceleration along x-axis

G_{YL} = Tolerable Acceleration along y-axis

G_{ZL} = Tolerable Acceleration along z-axis accelerations will be averaged over a time duration of 50 msec. The relationship between severity-index and injury levels will be discussed in a later section. Tolerable accelerations suggested by Weaver (12) for use in the severity-index equation are shown in Table 15.

TABLE 19

TOLERABLE AUTOMOBILE ACCELERATIONS
(After Weaver 12)

Degree of Occupant Restraint	Accelerations		
	G_{YL}	G_{XL}	G_{ZL}
Unrestrained	5	7	6
Lap Belt Only	9	12	10
Lap Belt and Shoulder Harness	15	20	17

Since the computer models of the vehicle were one-dimensional, the lateral acceleration term (G_{lat}) and the vertical acceleration term (G_{long}) were set equal to zero in the subsequent work.

SEVERITY-INDEX RELATIONSHIPS

The criteria used in the majority of the research work conducted during the past decade for evaluating the safety aspects of roadside hazard improvements were based on levels of vehicle acceleration that would be tolerable to an unrestrained occupant. One method used to accomplish this task was to define a Severity-Index which was computed as the ratio of the measured resultant automobile acceleration to the resultant "tolerable" automobile acceleration (see Eq. 3). An improvement that resulted in a Severity-Index value of one or less was considered to be safe; whereas, an improvement resulting in a Severity-Index value greater than one was considered to be unsafe. The work to follow will expand the existing technology to include the probability of occurrence of roadside injury type accidents.

Injury Probability

An indepth discussion on a tentative relationship between Severity-Index and the probability of occurrence of injury type accidents was recently presented by Post (13) to the Transportation Research Board. The relationship established for injury probability is shown in Table 20. For simplicity purposes in this study, the histogram relationship was approximated by the two linear relationships as shown in Figure 32.

TABLE 20

RELATIONSHIP BETWEEN SEVERITY-INDEX
AND PROBABILITY OF INJURY ACCIDENTS

(After Post 13)

Severity-Index (SI)	Probability of Injury Accident
$SI \leq 0.5$	0.1
$0.5 < SI \leq 1.0$	0.3
$1.0 < SI \leq 1.5$	0.5
$1.5 < SI \leq 2.0$	0.7
$2.0 < SI \leq 2.5$	0.8
$2.5 < SI$	1.0

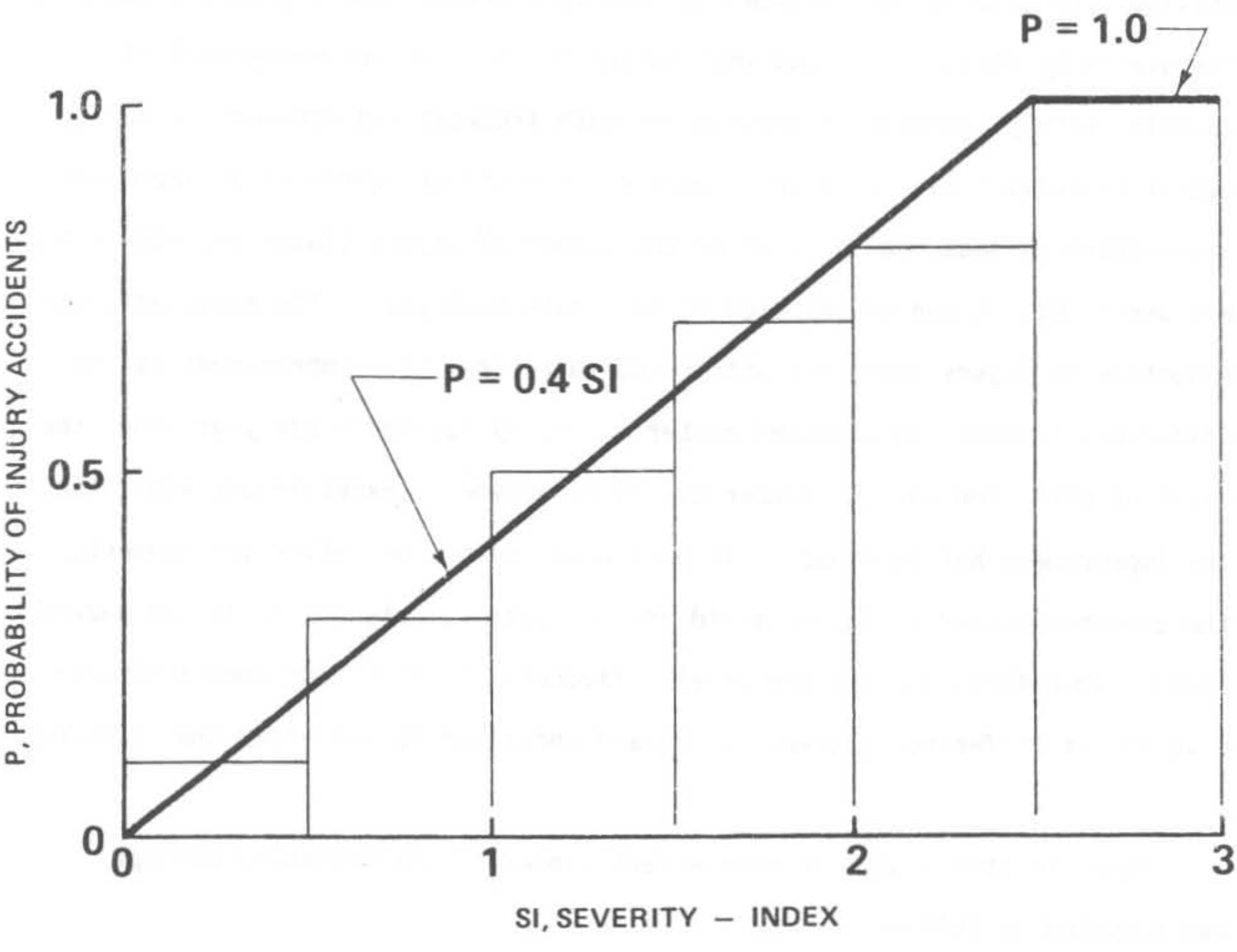


FIGURE 32
RELATIONSHIP BETWEEN SEVERITY – INDEX AND PROBABILITY OF INJURY ACCIDENTS

COST-EFFECTIVENESS ANALYSIS

The cost-effectiveness of an improvement alternative is its annualized cost per unit of improvement (effectiveness) it provides. In general, the lower this cost, the more cost-effective the alternative.

The method used to calculate the cost-effectiveness of the UNL breakaway utility pole concept was derived from the cost-effectiveness priority approach formulated by Glennon (14) and implemented in Texas in the management of roadside safety improvement programs on both freeways and non-controlled access roadways (15). With this approach, the effectiveness of an improvement alternative is measured in terms of the number of injury (fatal and non-fatal) accidents that it can be expected to eliminate each year. The expected annual reduction in injury accidents attributed to a particular improvement is the difference between the expected number of injury accidents per year under the existing condition and the number of injury accidents expected per year after the improvement has been made. In each case, before and after improvement, the expected number of injury accidents per year is referred to as the hazard index. Therefore, the measure of effectiveness of given improvement alternative is the difference between the hazard index before and after the improvement.

Thus, in this study the cost-effectiveness of the breakaway concept was computed as follows:

$$CE = \frac{C_I - C_E}{H_E - H_I} \qquad \text{---Eq.19}$$

where:

CE = cost-effectiveness of breakaway pole, cost to reduce one injury accident (dollars/injury accident reduced/mile);

C_I = annualized cost of breakaway pole (dollars/year/mile);

C_E = annualized cost of nonbreakaway pole (dollars/year/mile);

H_E = hazard index of nonbreakaway pole (expected number of injury accidents/year/mile);

H_I = hazard index of breakaway pole (expected number of injury accidents/year/mile).

The annualized cost of the breakaway pole includes normal and collision maintenance costs as well as the first cost of retrofitting the pole to make it a breakaway pole. The annualized cost of the nonbreakaway pole is cost of maintaining it, which includes both normal and collision maintenance costs.

A description of the procedure used to calculate the hazard indices and annualized costs follows.

Hazard Index

The generalized equation used to compute the hazard index of a utility pole is:

$$H_i = E \cdot P(C/E) \cdot \sum_v P_v P_v (I/C)_i \qquad \text{---Eq. 20}$$

where:

H_i = hazard index for utility pole of type i, breakaway or non-breakaway (expected number of injury accidents/year/mile);

E = encroachment rate (number of roadside encroachments/year/mile);

$P(C/E)$ = probability that pole will be struck given that an encroachment has occurred;

P_v = probability of an impact at speed v given that an encroachment has occurred;

$P_v(I/C)_i$ = probability of an injury accident given that a pole of type i has been struck by a vehicle encroaching at speed v;

v = speed of encroachment (mph).

The method by which each of the independent variables in this equation is computed is described below.

Encroachment Rate

Knowledge of the rate at which vehicles encroach on the roadside of various types of highways is very limited. In fact the only pure encroachment data available are that of Hutchinson and Kennedy (16), which were collected on freeway medians. More recently Glennon (17) has estimated encroachment rates for different types of highways as linear functions of average daily traffic (ADT). These relationships were derived from an analysis of roadside accident rates for different types of highways and a comparison of the freeway encroachment rate determined by Hutchinson and Kennedy and the freeway roadside accident rate in Missouri.

In this analysis the encroachment-rate-versus-ADT relationship determined by Glennon for urban arterial streets was used. This relationship is:

$$E = 0.000667\ ADT \qquad \text{---Eq. 21}$$

where:

E = encroachment rate (number of encroachments on each side of the street/year/mile);

ADT = average daily traffic (both directions).

This relationship assumes a 50-50 direction split in ADT.

Probability of Collision

The probability that a vehicle which encroaches on the roadside will collide with a utility pole is the product of two other conditional probabilities expressed as follows:

$$P(C/E) = P(X/E)\ P(C/X) \qquad \text{---Eq. 22}$$

where:

$P(C/E)$ = probability that a pole will be struck given that an encroachment has occurred;

$P(X/E)$ = probability that path of vehicle will intersect location of a pole given an encroachment has occurred;

$P(C/X)$ = probability of vehicle colliding with pole given that vehicle is on an intersecting path.

The probability that an encroaching vehicle will be on a path that intersects the location of a utility pole is proportional to the longitudinal length of the street within which this can occur. This longitudinal length is a function of the number, spacing, and diameter of utility poles, the width of the vehicle, and the angle of encroachment. This length effect of a utility pole for a given encroachment is:

$$L = d + w\ (\csc\Theta) + d\ (\cot\Theta) \qquad \text{---Eq. 23}$$

where:

L = longitudinal length of street within which the path of a vehicle encroachment at angle Θ will intersect the location of the utility pole (feet);

d = diameter of the utility pole (feet);

w = width of encroaching vehicle (feet);

Θ = angle of encroachment (feet).

Therefore, assuming that the longitudinal distribution of encroachment along a street is uniform, the probability that an encroaching vehicle will be on a path that intersects the location of a utility pole is:

$$P(CS/E) = \frac{d + w\ (\csc\Theta) + d\ (\cot\Theta)}{S} \qquad \text{---Eq. 24}$$

where:

S = spacing between utility poles (feet);

P(X/E), d, w, Θ = same as previously defined.

Evaluating Equation 8 for the pole spacing (150 ft.) which was used in the full-scale test and the average encroachment angle (7^o) found by Glennon (17) for urban arterial the probability is 0.389 that the path of an encroaching vehicle six feet wide will intersect the location of a utility pole one foot in diameter, which was the value used in this analysis.

The probability that an encroaching vehicle on an intersecting path will collide with a utility pole is a function of the lateral distance between the outside edge of the travelled way and the location of the utility pole. The greater this distance, the further the vehicle must travel along the path to reach the location and the less likely it is that it will collide with a pole. For the purpose of this analysis, the probability values shown in Table 21 were used for this probability. These values were derived from the distribution of the lateral extent of encroachments on urban arterial streets estimated by Glennon (17).

Probability of Injury Accident

The probability of an injury accident given that a collision with a utility pole has occurred is a function of the severity index of the impact.

TABLE 21 - LATERAL EXTENT OF ENCROACHMENT PROBABILITIES ON URBAN ARTERIAL STREET

Lateral Distance of Utility Pole From Edge of Traveled Way (feet)	Probability of Vehicle on Intersecting Path Colliding With Utility Pole[a]
0 - 5	.88
5 - 10	.66
10 - 15	.48
15 - 20	.34
20 - 25	.23
25 - 30	.15
>30	.06

(a) Derived from Glennon (<u>17</u>).

In turn, the severity index depends on the speed of impact, the type of pole (i.e., breakaway or nonbreakaway), and the size of the vehicle (i.e., 4,500 lbs or 2,250 lbs). The probability of injury accident for the various impact-speed, pole-type, vehicle-size combinations considered in this study are shown in Tables 11, 12, and 13. The procedures used to compute these values were described in a previous section of this report.

Impact Speed Probabilities

The impact speed probabilities used to compute hazard indices were determined based on the assumption of normally distributed impact speeds. A mean speed of 22.5 mph and a standard deviation of ± 5 mph were used.

Annualized Cost

Lincoln Electric System estimated that it would cost an average of $15 to retrofit a utility pole to make it breakaway. This cost includes labor, materials, and travel costs. At the pole spacing of 150 feet, which was used in the full-scale tests, it would cost about $540 per mile to retrofit a line of utility poles located on one side of the street. Using a 15-year life, 7% interest rate, and a zero salvage value, the annualized cost of retrofitting is approximately $60/year/mile. The estimated life of a utility pole is around 30 years; therefore, the use of a 15-year life is based on the assumption that retrofitting existing poles will occur on the average 15 years after the poles were installed.

For the purposes of this analysis, the annual collision and normal maintenance costs of breakaway poles were assumed to be the same as those of the nonbreakaway poles. Therefore, the total annualized cost of breakaway poles used was $60/year/mile.

Evaluation

The hazard-index and annualized-cost data presented in the preceding sections were used to compute the cost-effectivenss of the UNL breakaway concept. An ADT of 20,000 was assumed, which corresponds to an encroachment frequency of 13.3 encroachments on one side of an urban arterial street per year per mile. Computations were done for both a 4,500-lb vehicle and a 2,250-lb vehicle. Also, cost-effectiveness values were calculated over a range of lateral offsets of the pole from the edge of the traveled way. The results of these computations are presented in Tables 20 and 21.

On the basis of these results, it appears that the breakaway concept is very cost effective particularly for utility poles located close to the street. Also, it appears to be more cost effective in the case of the heavier vehicle. However, even for the lighter vehicle it provides over a 95% probability that a reduction in injury accidents will result from its application to utility poles within 20 feet from the street.

It should be remembered that the cost-effectiveness values shown in Tables 22 and 23 are for an ADT of 20,000. These values are inversely proportional to ADT. Therefore, the cost-effectiveness of the concept would be better than that indicated by the values in these tables if the ADT were higher, and vice versa. Also, it should be noted that in general the results are independent of pole spacing, because the change in the effectiveness (i.e., the reduction in hazard index) of the concept due to a change in pole spacing is the same as that in annualized cost caused by the same change in spacing. For example, if the pole spacing were doubled, both the reduction in hazard index and the annualized cost would be cut in half; and thus, the cost-effectiveness value would remain the same.

TABLE 22 - COST-EFFECTIVENESS OF BREAKAWAY UTILITY POLE - 4,500 lb Vehicle[(a)]

Lateral Offset (feet)	HI_E [(b)]	HI_I [(c)]	$HI_E - HI_I$	Cost-Effectiveness Value[(d)] ($/injury accid. reduced/yr/mi)	Probability of Zero Injury Accident Reduction [(e)]
0 - 5	3.02	2.15	.88	70	.000002
5 - 10	2.27	1.62	.65	90	.00006
10 - 15	1.65	1.18	.47	130	.0009
15 - 20	1.17	.83	.34	180	.006
20 - 25	.79	.56	.23	260	.03
25 - 30	.52	.37	.15	400	.11
>30	.21	.15	.06	1,000	.41

(a) Based on 20,000 ADT and 150-foot pole spacing.

(b) HI_E = hazard index of nonbreakaway pole.

(c) HI_I = hazard index of breakaway pole.

(d) Annualized cost of retrofitting pole = $60 /year/mi

(e) Based on 15-year life and Poisson distribution of accident occurrence.

TABLE 23 - COST-EFFECTIVENESS OF BREAKAWAY

UTILITY POLE - 2,250 lb Vehicle[a]

Lateral Offset (feet)	HI_E [b]	HI_I [c]	HI_E-HI_I	Cost-Effectiveness Value[d] ($/injury accid. reduced/yr/mi)	Probability of Zero Injury Accident Reduction [e]
0 - 5	3.81	3.25	.56	110	.0002
5 - 10	2.86	2.44	.42	140	.002
10 - 15	2.08	1.77	.31	190	.01
15 - 20	1.47	1.26	.21	290	.04
20 - 25	1.00	.85	.15	400	.11
25 - 30	.65	.55	.10	600	.22
>30	.26	.22	.04	1,500	.55

(a) Based on 20,000 ADT and 150-foot pole spacing.

(b) HI_E = hazard index of nonbreakaway pole.

(c) HI_I = hazard index of breakaway pole.

(d) Annualized cost of retrofitting pole = $60/year/mi

(e) Based on 15-year life and Poisson distribution of accident occurrence.

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

During the past several years considerable attention has been given to improving roadside safety by removing obstacles from the immediate vicinity of the traveled way. In many cases where these obstacles could not be removed, or relocated, the obstacles were modified to break away when struck by a vehicle. Research and accident experience have shown that breakaway sign supports and luminaire supports are effective in reducing the severity of vehicle impacts. However, not until recently has much attention been given to utility poles. Utility poles represent one of the most serious roadside hazards, particularly in urban areas, because of the relatively high collision frequency and the relatively high impact severity.

In February 1978, a concept for a breakaway utility pole was proposed by the Transportation Research Program at the University of Nebraska-Lincoln (UNL). During the next year, meetings were held with representatives of the Lincoln Electric System and Lincoln Telephone and Telegraph Company as well as the Nebraska Department of Roads, City of Lincoln, and Federal Highway Administration. The purpose of these meetings was to discuss the proposed concept and to solicit the involvement of these organizations in a study of its feasibility. Based on the interest expressed at these meetings, the Department of Civil Engineering and the Engineering Research Center at the UNL provided funding for such a study.

The objective of this study was to determine the feasibility of the UNL breakaway utility pole concept. A series of scale-model, pendulum, and full-scale vehicle crash tests were conducted to: (1) gain an understanding of the mechanics involved, (2) test the physical realizability of the concept, and (3) determine the degree to which it reduces impact severity. In addition, a computer simulation model was developed and validated with the data obtained from these tests. The model was then used to evaluate the performance of the concept for a variety of pole configurations and impact conditions. Based on the estimates of impact severity reduction from the computer simulations and full-scale tests, the potential cost-effectiveness of implementing the breakaway concept was determined.

From the results of this accident study, it is apparent that utility pole accidents are a serious problem in Lincoln, particularly at night and during the winter months when they are most likely to occur. The 40-ft. wooden utility pole is the type most commonly installed along arterial streets in Lincoln and consequently was the type most frequently struck. Thus this type of utility pole was selected for testing the UNL breakaway concept. Analysis of the most likely impact conditions indicated that the testing be conducted at impact speeds of 35 mph or less and impact angles of 30 degrees or less.

Compared to fixed object accidents in urban areas in Nebraska during 1978, wooden utility pole accidents in Lincoln had a higher than average severity. Also, as expected, the severity of these utility pole accidents generally increased with higher impact speeds, larger poles, and lighter vehicles.

The computer model program developed and validated in this study was used to compute the vehicle decelerations, vehicle momentum changes, vehicle crushing, and time and type of failure occurring at the lower and upper breakaway joints of the utility pole.

The impact severities computed for non-breakaway and breakaway utility poles showed that:

1. Breakaway utility poles are effective in reducing injury accidents.
2. Standard size vehicle impacts are less severe than subcompact vehicle impacts.
3. A standard size vehicle colliding with a non-breakaway utility pole is equal in severity to a subcompact size vehicle colliding with a breakaway utility pole.

No attempt was made in this study to monitor secondary impacts between the upper portion of the vehicle body and the two rigid body portions of the pole. Secondary impacts occurred in all the simulation runs when the upper breakaway joint was located at 7 ft. above groundline. To gain insight into the severity of secondary impacts, graphs were made of the trajectories of the two rigid body portions of the pole in relation to the outline shadow of a subcompact vehicle (1974 Vega GT). Based on an examination of these graphical plots, the following predictions were made:

1. The center-of-gravity of the 7 ft. "breakaway stub" section of the pole is high enough so that the upper end of the stub will not penetrate through the vehicle windshield, but will instead, land on the vehicle front hood and roof. This situation exists for all the impact speeds considered.
2. The upper portion of the breakaway pole (portion above upper breakaway joint: will strike the back windshield of the vehicle under the low impact speed of 15 mph. This situation could result in injuries in the rear seat.
3. The upper portion of the breakaway pole will most likely strike the trunk of the vehicle under an impact speed of 20 mph. This situation should not result in any injuries.

FULL-SCALE TEST CONCLUSIONS

A number of conclusions and comments on the full-scale tests were noted after review of the full-scale tests.

1. The breakaway concept preposed by the University of Nebraska appears to work best with the upper breakaway joint at 8 ft. or less above ground level. Dynamic analysis of the pole may improve this conclusion.

2. There is enough flexibility in the pole as modified by the breakaway concept so as to insure low probability of injury in a collision. This is true even when the upper breakaway joint does not fail.
3. A "worst case" failure mode occurred in Test No. 3 in which neither breakaway joint failed. Even under these conditions the probability of injury was significantly less than an unmodified pole.

On the basis of the cost-effectiveness analyses, it appears that the breakaway concept is very cost effective particularly for utility poles located within 10 ft. of the street. Also, the design concept appears to be more cost-effective in the case of the heavier 4,500 lb. vehicle. However, even for the lighter 2,250 lb. vehicle, the breakaway concept provides over a 95% probability that a reduction in injury accidents will result from retrofitting utility poles within 20 feet from the street.

FUTURE RESEARCH AND DEVELOPMENT WORK

This study of limited scope (Phase I) has demonstrated that (a) the breakaway utility pole stub concept is feasible and cost-effective, and (b) additional research and development (R&D) work is warranted. A work plan, schedule, and cost estimate for future Phase II and III R&D follows.

Work Tasks

Phase II Study

Task 1. Conduct 10 full-scale static tests on 40 ft. Class 4 Yellow Pine utility poles with breakaway joints to determine:

(a) Ultimate bending strength of breakaway joints with minimum required section modulus to carry ice and wind loadings.

(b) Ultimate shearing strength of breakaway joints with area corresponding to the minimum required section modulus.

Task 2. Modify computer model developed in Phase I Study

(a) Idealize breakaway pole as 4 or more rigid bodies to better reporesent elastic bending in area of upper breakaway joint.

(b) Monitor secondary vehicle body-pole impacts.

(c) Validate computer model with full-scale tests 1 and 2 in Phase I Study.

Task 3. Conduct 5 full-scale tests on 40 ft. Class 4 breakaway utility poles using subcompact vehicle (2,250 lbs.) at impact speeds of 15, 20, and 25 mph.

Task 4. Validate computer model with results from high-speed film analyses of full-scale tests conducted in Task 3.

FIGURE 33

ROADSIDE HAZARD INVENTORY FORM

NEBRASKA DEPARTMENT OF ROADS
LINCOLN, NEBRASKA

Inventory Conducted by ______________________ Date ______________

HIGHWAY (BOX 1)

Highway Design Number	Highway Number	Design Speed (mph)	ADT	Lane Width (ft)	Usable Shoulder Width (ft)	Width Shoulder Surfacing (ft)	Median Width (ft)	Deg. of Curve	Grade (%) UP	Grade (%) DN	Shoulder Drop-off (in)	Condition Non-Paved Shoulder
1 2 3	4 5 6 7	8 9	10 11 12 13 14	15 16	17 18	19 20	21 22	23	24	25	26	27

Highway Design Number: 1. DR 2. DM 3. ROA 4. RC 5. RL

Highway Number: 1. US 2. N 3. I 4. SEC

Condition Non-Paved Shoulder: 1. Smooth 2. Rough

HAZARD CLASSIFICATION (BOX 2)

Description ______________________________

Hazard Number	Identification Code	Descriptor Code	Offset Code	Grouping Number
28 29 30 31	32 33	34 35	36	37 38

Offset Code: 1. Right Side 2. Left Side or Median

MILE POINT AT HAZARD (BOX 2)

Beginning	Ending
39 40 41 42 43 44	45 46 47 48 49 50

POINT HAZARDS (BOX 3)

	Offset (ft)	Width (ft)	Length (ft)	Drop Inlets Only: Height (in)	Drop Inlets Only: Depth (in)
1					
51	52 53	54 55	56 57 58 59	60 61	62 63

LONGITUDINAL HAZARDS (Guardrails, Bridgerails, Barrier Walls, and Curbs) (BOX 4)

	Offset (ft) Begin	Offset (ft) End	Top Height (in)	Post Spacing (ft)	Guardrail: Post Spacing if at Bridge End	Guardrail: Blockout	Guardrail: Rub Rail	Guardrail End Treatment: Beginning	Guardrail End Treatment: Ending
2									
51	52 53	54 55	56 57	58 59	60	61	62	63	64

Post Spacing if at Bridge End: 1. Reduced 2. Not Reduced

Blockout: 1. No. 2. Yes

Rub Rail: 1. No 2. Yes

Guardrail End Treatment:
1. Not Anchored (to ground or Bridge)
2. Anchored (to ground or Bridge)
3. Anchored Turndown (not breakaway)
4. Breakaway Terminal Design

SLOPE HAZARDS (Median Ditches, Roadside Ditches, Fill Ditches, and Cut Slopes) (BOX 5)

	Hinge Point Offset (ft)	Front Slope (average)	Front Slope Height (ft)	Ditch Width (ft)	Back Slope (average)	Back Slope Height (ft)	Condition of Slopes	Depth of Water
3		:1			:1			
51	52 53	54	55 56	57 58	59	60 61	62	63

Condition of Slopes: 1. Smooth 2. Rough

Depth of Water: 1. None 2. Less than 2 ft. 3. Greater than 2 ft.

BOX 6

DATE Mo	DATE Day	DATE Yr	IBM Card Type
			1
70 71	72 73	74 75	80

Recommendations ______________________________
____
____

FIGURE 34

ROADSIDE HAZARD IMPROVEMENT FORM

NEBRASKA DEPARTMENT OF ROADS
LINCOLN, NEBRASKA

Improvement Recommended by ____________ **Date** ____________

HIGHWAY (BOX 1)

Highway Design Number: 1 — 2 3
1 DR SRL
2 DM
3 ROA
4 RC
5 RL

Highway Number: 4 — 5 6 7
1 US
2 N
3 I
4 SEC

Design Speed (mph): 8 9

ADT: 10 11 12 13 14

Hazard Number ____________
Hazard Group Number ____________
Improvement Alternative Number ____________

COSTS (BOX 2)

Capital Costs ($1,000): 15 16 17 18 19

Collision Maintenance ($100/accid.): Hazard 20 21 22; Improvement 23 24 25

Normal Maintenance ($100/yr): Hazard 26 27; Improvement 28 29

POINT HAZARD IMPROVEMENTS (BOX 3)

[1] 30 [1] 31 Alleviate Hazard — 32: 1 Remove; 2 Make Breakaway and/or Relocate; 3 Reconstruct Inlet to Safe Design; 4 Reconstruct Cross Drainage System

[1] 30 [2] 31 Install Traffic Barrier (complete Box A) — 32 33 Descriptor Code — 34 35 36 37 Length (ft)

[1] 30 [3] 31 Install Energy Attenuator — 32 33 Descriptor Code

LONGITUDINAL HAZARD IMPROVEMENTS (BOX 4)

[2] 30 [1] 31 Curb — 32: 1. Remove and Regrade; 2. Install Wedge Modification

[2] 30 [2] 31 Traffic Barrier — 32: 1. Remove; 2. Modify (complete Boxes A, B & C); 3. Replace with New Design (complete Boxes A, B & C) — 33 34 Descriptor Code (New Design Only)

[2] 30 [3] 31 Bridgerail — 32: 1. Modify; 2. Replace with New Design — 33 34 Descriptor Code

SLOPE IMPROVEMENTS (BOX 5)

[3] 30 [1] 31 Install Traffic Barrier (complete Boxes A and C) — 32: 1 At Bridge; 2. Not at Bridge — 33 34 Descriptor Code

[3] 30 [2] 31 Modify (complete Box C)

Hinge Point Offset (ft)	Front Slope (average)	Front Slope Height (ft)	Ditch Width (ft)	Back Slope (average)	Back Slope Height (ft)	Condition of Slopes	Depth of Water (ft)
32 33	34 :1	35 36	37 38	39 :1	40 41	42	43
						1 Smooth 2. Rough	1. None 2 Less than 2 ft. 3. Greater than 2 ft

NO IMPROVEMENT (BOX 6)

[4] 30

BOX A (TRAFFIC BARRIER MODIFICATIONS)

Offset (ft) Begin	Offset (ft) End	Top Height (in)	Post Spacing (ft)	Guardrail: Post Spacing at Bridge End	Guardrail: Block Out	Guardrail: Rub Rail	Guardrail End Treatment: Beginning	Guardrail End Treatment: Ending
48 49	50 51	52 53	54 55	56	57	58	59	60
				1. Reduced 2. Not Reduced	1. No 2. Yes	1. No 2. Yes		

Guardrail End Treatment: 1. Not Anchored (to ground or bridge); 2. Anchored (to ground or bridge); 3. Anchored Turndown (not breakaway); 4. Breakaway Terminal Design

BOX B (CHANGES TO EXISTING GUARDRAIL)

Beginning 61: 1 Lengthen; 2 Shorten
Ending 62: 1. Lengthen; 2. Shorten
Change in Length (ft) 63 64

BOX C (MILE POINT OF CHANGE)

Beginning 65 66 67 68 69 70
Ending 71 72 73 74 75 76

BOX 7

79: 1 End of Group; 2 End of Group and Program

[2] 80 IBM Card Type

Task 5. Conduct 5 full-scale field static tests on retrofitted utility poles with breakaway joints to determine the structural adequacy of the poles under heavy ice and wind loading conditions as specified in ANSI (4).

Task 6. Develop design criteria for retrofitting existing wood utility poles with breakaway joints using the cost-effectiveness (C/E) program developed by Post (8) for the Nebraska Department of Roads (NDR). The Roadside Hazard Inventory and Improvement Coding Forms developed in the NDR study are shown in Figures 33 and 34. Utility poles would fall under the "Point Hazard" category. Additional subroutines would have to be developed to use this program on breakaway utility poles. A computer model parameter study (Table will be conducted to compute severity-indices to be used in the C/E model.

Task 7. Determine feasibility of applying and sealing liquid Fumigants in the lower breakaway joint of retrofitted utility poles in order to control internal decay fungi and insects above and below groundline. A paper on Fumigant treatment was published by Graham (9).

Task 8. Investigate the legal obstacles of who is responsible for retrofitting and maintaining breakaway utility poles. Also, investigate the legal obstacles associated with breakaway utility poles falling and injuring bystanders or causing secondary collisions.

Task 9. Prepare Interim Report of Task 1 through 8.

Note: If findings in Interim Report are satisfactory and approved by the sponsors, then continue with Phase III Study; otherwise, terminate the project.

TABLE 24

COMPUTER MODEL PARAMETER STUDY

(324 Simulations)

Variable	Conditions
Automobile Sizes	1500[a], 2000, 2500[a], 3000, and 4000 lbs
Impact Speeds	10[a], 15, 20, 25[a], 30 and 35[a] mph
Pole Lengths	30, 35[a], 40, 45[a], and 50 ft
Breakaway Joints	S_{min}, 1.25 S_{min}
Breakaway Joint Heights	7 and 8 ft
Soil Types	2 type soils [standard compaction & moisture content
Wire Arrangements	Non-breakaway Connections 1 crossarm 2 crossarms Breakaway Connections 1 crossarm

a. Interpolated

Phase III Study

Task 10. Retrofit existing utility poles with breakaway joints in high accident locations.

Task 11. Evaluate impact performance of retrofitting breakaway utility poles in Task 10. Damage done to conductors and insulators will also be evaluated in this task.

Task 12. Update design criteria in Task 6 of the Phase II Study.

Task 13. Prepare final report.

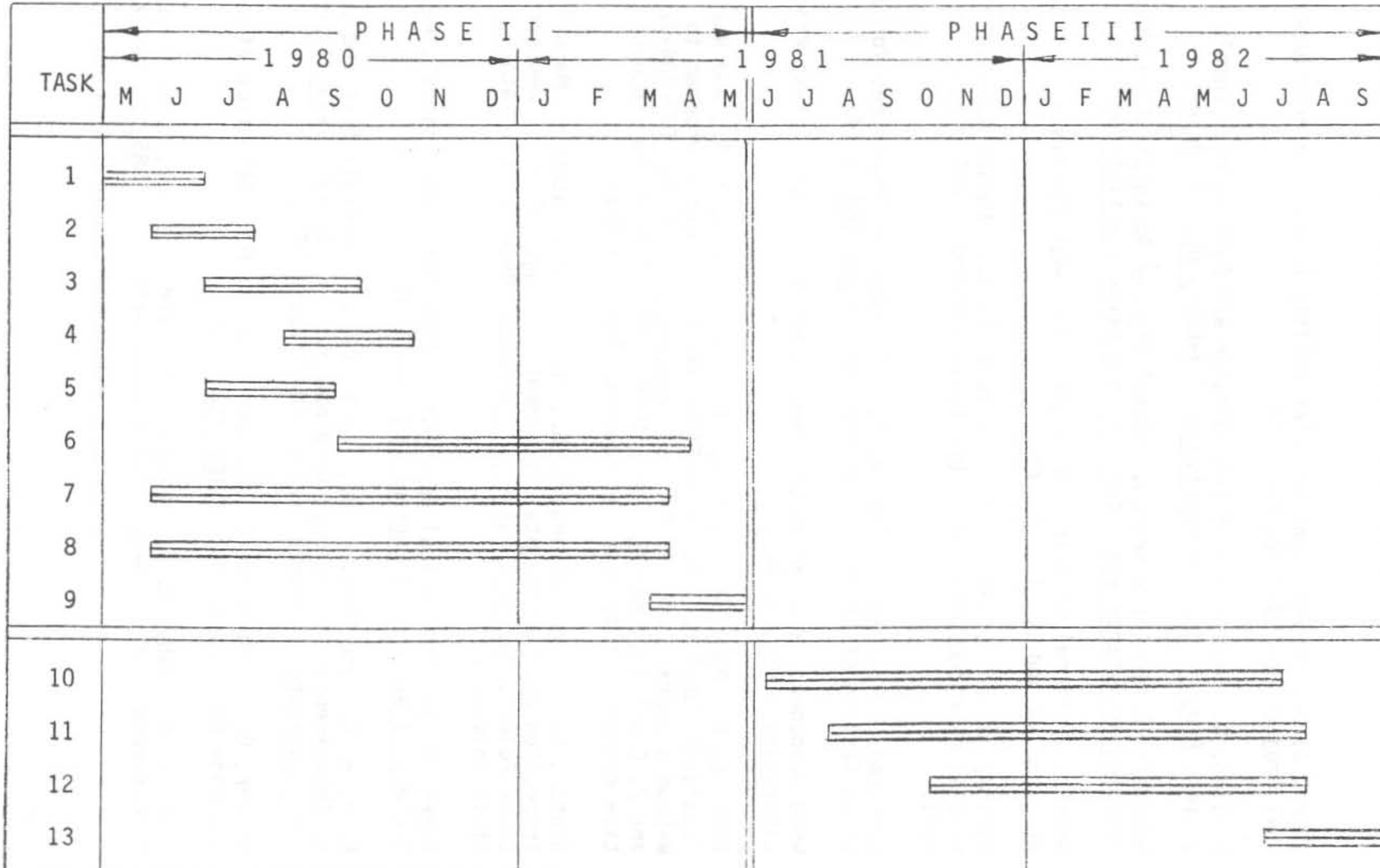
Work Schedule

A work schedule of the Phase II and III Studies is presented in Table 25. The total study would require 30 months to complete with 12 months spent in Phase II.

Cost Estimate

It is estimated that Phase II would require 2 man-yrs of effort and Phase III would require 1 man-yr of effort.

TABLE 25. WORK SCHEDULE



REFERENCES

1. Labra, J. J., "Development of Safer Utility Poles", Interim Report, SwRI Project No. 03-4502, Dec 1977.

2. Redding, D., Supervisor of Transmission and Substation, Lincoln Electric System, Project Reporesentative on Breakaway Utility Poles.

3. McDivett, Office of Research, Federal Highway Administration, Wash. D.C., Provided assistance and materials in breakaway utility poles.

4. American National Standard Institute: National Electrical Safety Code, Sections 25 and 26, 1977 Edition.

5. Marinez, J. E., Olson, R. M., and Post, E. R., "Impact Response of Overhead Sign Bridges Mounted on Breakaway Supports", HRR 346, pp 35-46, 1971.

6. Bronstad, M. E., and Michie, J. D., "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances", NCHRP 153, 1974.

7. Wood Handbook: Wood as an Engineering Material, U.S. Forest Products Laboratory, 1974, pp 4-13.

8. Post, E. R., Ruby, R. J., McCoy, P. T., Chastain, P. A., and Rupp, S. S., "Guardrail Utilization: Cost-Effectiveness Computer Program to Analyze W-Beam Guardrail on Fill Slopes", Research Report No. TRP-004-78, Vol. 1 and 2, Civil Engineering Dept., University of Nebraska-Lincoln, (cooperative research study with the Nebraska Dept. of Roads).

9. Graham, R. D., and Helsing, G. G., "Wood Pole Maintenance Manual: Inspection and Supplemental Treatment of Douglas-Fir and Western Red Cedar Poles", Research Bulletin 24, Forest Research Laboratory, Oregon State University.

10. Emori, R. I., "Analytical Approach to Automobile Collisions", Paper 680016 Society of Automotive Engineering, Jan 1968.

11. Ross, H. E., and Post, E. R., "Criteria for Guardrail Need and Location on Embankments--Volume One, Development of Criteria", Texas Transporta tion Institute, Research Report 140-4, April 1972.

12. Weaver, G. D., Marquis, E. L., and Olson, R. M., "Selection of Safe Roadside Cross Sections", NCHRP 158, 1975.

13. Post, E. R., Ruby, R. J., McCoy, P. T., and Coolidge, D. O., "Cost-Effectiveness of Driveway Slope Improvements", TRB 685, pp 14-19.

14. Glennon, J. C., "Roadside Safety Improvement Programs on Freeways: A Cost-Effectiveness Priority Approach", NCHRP 148, 1974.

15. Weaver, G. D., Woods, D. L., and Post, E. R., "Cost-Effectiveness Analysis of Roadside Safety Improvements", TRB 543, pp 1-15, 1975.

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

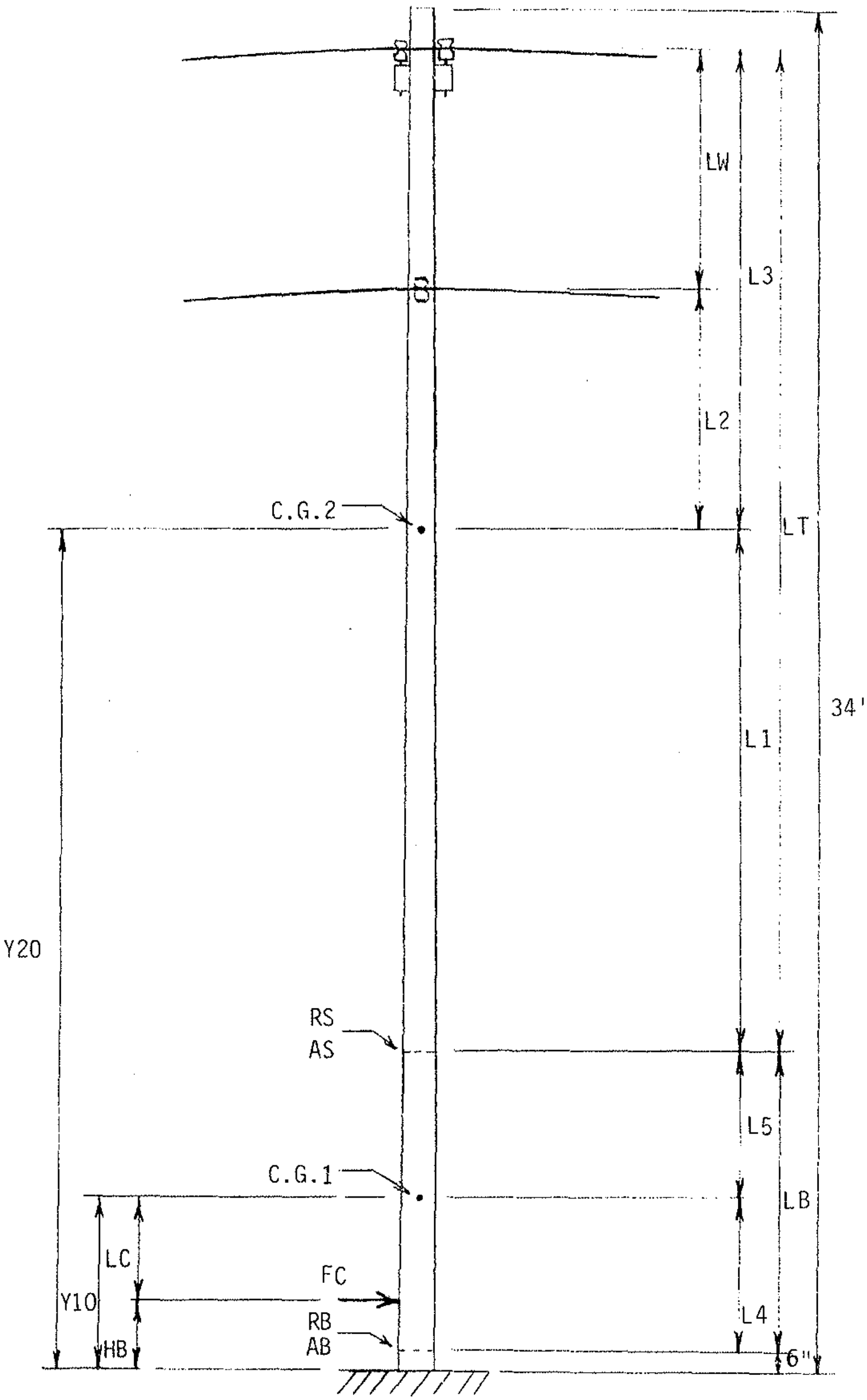
17. Glennon, J. C. and Wilton, C. J., "Effectiveness of Roadside Safety Improvements: Vol. 1 - A Methodology for Determining the Safety Effectiveness of Improvements on All Classes of Highways", Federal Highway Administration, Report No. FHWA-RD-75-23, November, 1974.

18. Standard Summary of Nebraska Motor Vehicle Traffic Accidents, Nebraska Department of Roads, 1978.

19. Graham, M. D., Michie, J. D., Nordlin, E. F., and Viner, J. G., "Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances", NCHRP 191, 1978. This is an update of Ref. (6).

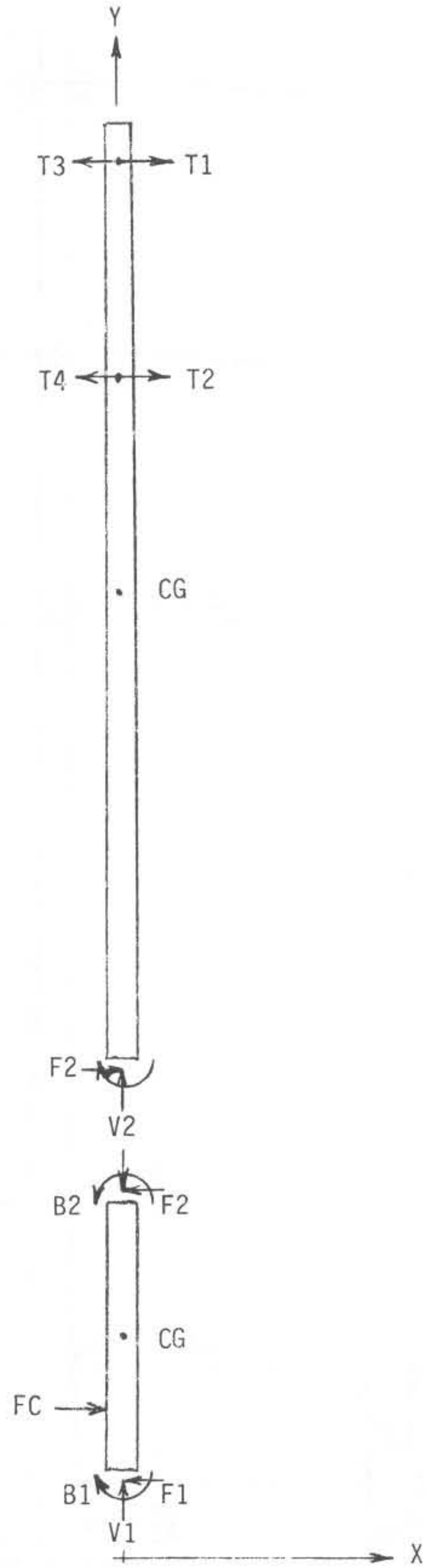
APPENDIX A

COMPUTER MODEL VARIABLE NAMES



GEOMETRIC CONSTANTS FOR COMPUTER SIMULATION

Fig. A1



FREE BODY DIAGRAM FOR COMPUTER SIMULATION

Fig. A2

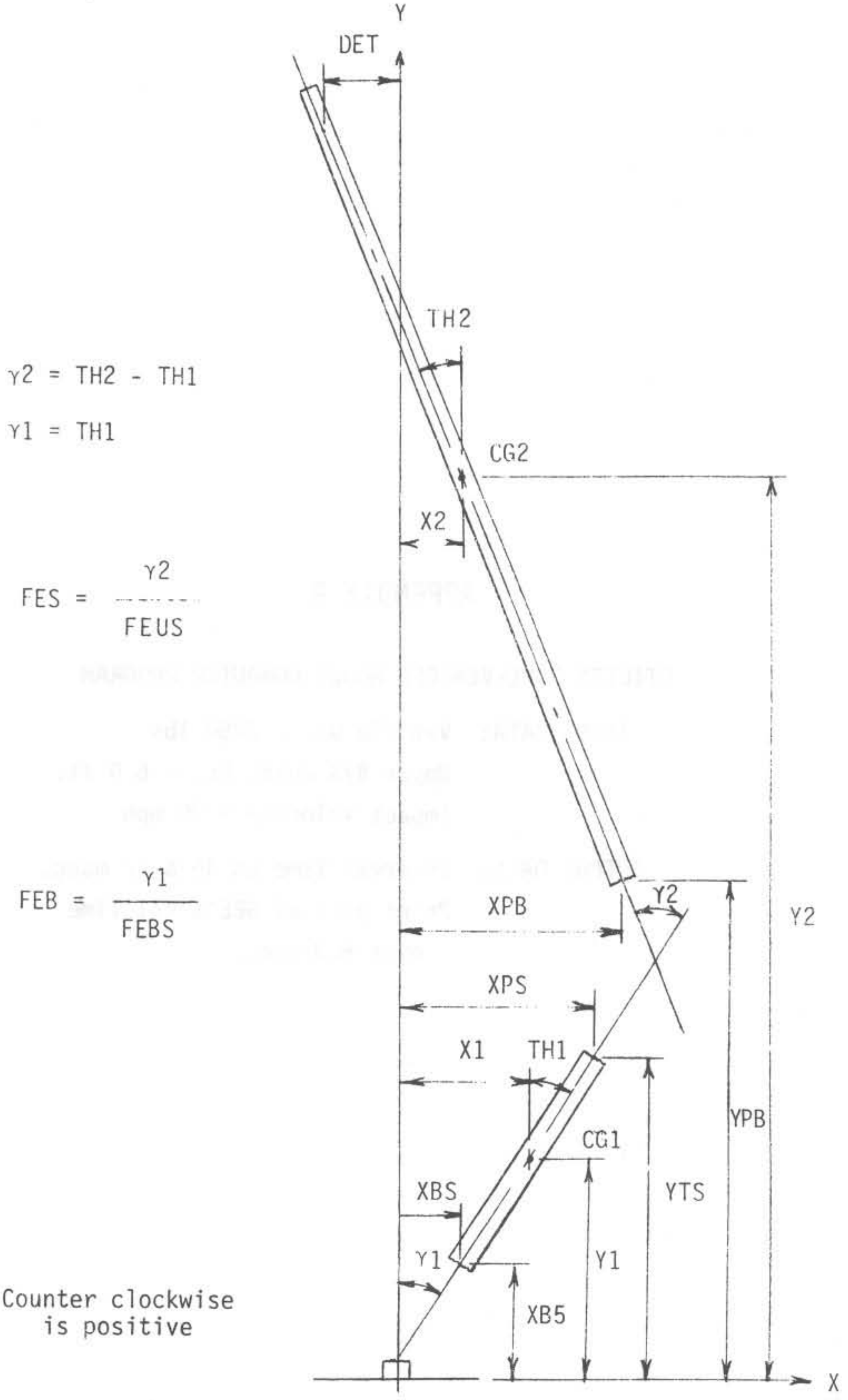


Fig. A3
COORDINATES AND DISPLACEMENTS FOR
COMPUTER SIMULATION

APPENDIX B

UTILITY POLE-VEHICLE MODEL COMPUTER PROGRAM

INPUT DATA: Vehicle Wt. = 2250 lbs.
Upper B/A Joint Ht. = 8.0 ft.
Impact Velocity = 20 mph

OUTPUT DATA: Interval Time at 46 & 47 msec.
Print plot of GEE's vs. Time
over 6.3 msec.

```
NITIAL
      CONSTANTS TM1=60000.,DET=5.,LW=72.,LT=318.,SCF2=1.,VEL=20.....
                HB=20.,RB=5.300, RT=3.35,RS=4.950,AB=25.5,...
                AS=20.8, GAM=.0260,C1=2.,F2MAX=4.16E4
      CONSTANTS E=1900000.,PS1=.626,PS2=.585,STRP=3000.,STRU=14000.....
                PI=3.141593,SCF=1.0,CH1=0.,CH2=0.,F1MAX=5.1E4,...
                TM2=20000.,LB=90.,WC=2250.

      XCDC=VEL*1.4667*12.
      INCON X1=0.,X2=0.,TH1=0.,TH2=0.,XC=0.,CSELC=0.
      FUNCTION MCM=0.,0., .4,.55,1.,1.,1.001,0.,10000.,0.
      YT=LT/2.
      L1=YT
      L2=LT-YT-LW
      L3=LT-YT
      Y20=LB+YT+6
      MT=GAM*PI*((RS+RT)/2.)**2*LT/386.
      IMT=MT*2.*YT**2/3.

      WT=MT*386.
      V20=WT
      YB=LB/2.
      MB=GAM*PI*((RB+RS)/2.)**2*LB/386.
      L4=YB
      L5=LB-YB
      LC=YB+6-HB
      Y10=YB+6
      WB=MB*386.

      IMB=MB*2.*YB*YB/3.

      V10=WT+WB

      ZS=4./3.*RS**3*PS2
      ZB=4./3.*RB**3*PS1
      IB=PI*RB**4/4.*PS1
      IS=PI*RS**4/4.*PS2
      SB=IB/RB
      SS=IS/RS

      MC=WC/386.
      KC=WC*18.5/12.
      BPS=STRP*SS
      BPB=STRP*SB
      BUS=STRU*ZS
      BUB=STRU*ZB
      FEUS=(5.*BPS**2+BUS*BPS)/((BUS+BPS)*E*IS)
      FEUB=(5.*BPB**2+BUB*BPB)/((BUB+BPB)*E*IB)

YNAMIC
  NOSORT

      XT1=X2-L3*SIN(TH2)
      XT2=X2-L2*SIN(TH2)
      XPB=X2+L1*SIN(TH2)
      YPB=Y2-L1*COS(TH2)
      XTS=X1-L5*SIN(TH1)
      YTS=Y1+L5*COS(TH1)
```

```
      XBS=X1+L4*SIN(TH1)
      YBS=Y1-L4*COS(TH1)

      T1=0.
      T2=0.
      T3=0.
      T4=0.
      IF(XT1.GE.DET)T3=TM1
      IF(XT1.LE.-DET)T1=TM1
      IF(XT2.GE.DET.AND.C1.GT.0.5)T4=TM2
      IF(XT2.LE.-DET.AND.C1.GT..5)T2=TM2
      IF(CH1.GT..99)SCF2=SCF
      FES=(TH2-TH1)/FEUS/SCF2
      B2=BUS*AFGEN(MOM,ABS(FES))
      IF(FES.LT.0.)B2=-B2
      KF2=2000.*AS/1.
      KV2=E*AS
      F2=KF2*SQRT((YPB-YTS)**2+(XPB-XTS)**2)
      V2=KV2*(YTS-YPB)+V20
      IF(ABS(B2).LT.1.E-15.AND.TIME.GT..005)CH2=1.
      IF(ABS(F2).GT.F2MAX.AND.TIME.GT..005)CH2=1.
      IF(CH2.LT..001)GOTO 10

      B2=0.
      F2=0.
      V2=0.
   10 CONTINUE

      FEB=TH1/FEUB
      B1=BUB*AFGEN(MOM,ABS(FEB))
      IF(FEB.LT.0.)B1=-B1
      KF1=2000.*AB/1.
      KV1=E*AB
      F1=KF1*XBS
      V1=-KV1*(YBS-6.)+V10
      IF(ABS(B1).LT.1.E-15.AND.TIME.GT..005)CH1=1.
      IF(ABS(F1).GT.F1MAX.AND.TIME.GT..005)CH1=1.
      IF(CH1.LT..001)GOTO 20

      B1=0.
      F1=0.
      V1=0.
   20 CONTINUE
      CDEL=ABS(XC-(X1+LC*SIN(TH1)))
      IF(CDEL.LE.CDELO.OR.XC.LT.(X1+LC*SIN(TH1)+CDELO))GOTO 30
      CDELO=CDEL
      FC=KC*CDEL
      GOTO 40
   30 FC=0.
   40 CONTINUE
      IF((Y1-LC*COS(TH1)).GT.(2.*FE))FC=0.
SORT
      XCDD=-FC/MC

      X1DD=(FC-(F1+F2)*COS(TH1)+(V2-V1)*SIN(TH1))/MB
      Y1DD=(-WB+(V1-V2)*COS(TH1)-(F2+F1)*SIN(TH1))/MB
      TH1DD=(B2-B1+FC*LC*COS(TH1)+L5*F2-L4*F1)/IMB

      X2DD=(T1+T2-T3-T4+F2*COS(TH2)-V2*SIN(TH2))/MT
      Y2DD=(-WT+F2*SIN(TH2)+V2*COS(TH2))/MT
      TH2DD=(-B2+L1*F2+(T4-T2)*COS(TH2)*L2+(T3-T1)*COS(TH2)*L3)/IM
```

```
      XCD=INTGRL(XCDS,XCDD)

      X1D=INTGRL(0.,X1DD)
      Y1D=INTGRL(0.,Y1DD)
      TH1D=INTGRL(0.,TH1DD)

      X2D=INTGRL(0.,X2DD)
      Y2D=INTGRL(0.,Y2DD)
      TH2D=INTGRL(0.,TH2DD)

      XC=INTGRL(0.,XCD)

      X1=INTGRL(0.,X1D)
      Y1=INTGRL(Y10,Y1D)
      TH1=INTGRL(0.,TH1D)

      X2=INTGRL(0.,X2D)
      Y2=INTGRL(Y20,Y2D)
      TH2=INTGRL(0.,TH2D)


      GEE=-XCDD/386.
      VEC=XCD/12./1.47
      DEG1=TH1*180./PI
      DEG2=TH2*180./PI

INAL

      IMP=(VCLD-XCD)*MC
      VCLD=XCD
      TIMER DELT=.0002, FINTIM=.60,PRDEL=.001,OUTDEL=.003
      METHOD RKSFX
      PRINT XC,GEE,VEC,CDELC,F1,B1,F2,B2,DEG1,FEB,DEG2,FES,...
            XFB,YPB,X2,Y2,XTS,YTS,X1,Y1,XBS,YBS

      PRTPLOT GEE(XC,VEC),XTS(XC),YTS(XC),XPB(XC),YPB(XC)
      END
      STOP
```

```
TIME  =  4.6000E-02     XC     =  1.4100E 01       GEE    =   2.1199E 01
                        F1     =  1.8815E 04       B1     =   1.5970E 06
                        DEG1   =  8.1381E-02       FEB    =   8.9068E-01
                        XPB    =  1.2773E 00       YPB    =   9.6000E 01
                        XTS    =  2.4109E-01       YTS    =   9.6000E 01
                        XBS    =  3.6892E-01       YBS    =   6.0000E 00

                        VEC    =  1.2440E 01       CDELC  =   1.3751E 01
                        F2     =  0.0              B2     =   0.0
                        DEG2   =  7.7997E-02       FES    =  -3.4592E-02
                        X2     =  1.0609E 00       Y2     =   2.5500E 02
                        X1     =  3.0500E-01       Y1     =   5.1000E 01

TIME  =  4.7000E-02     XC     =  1.4317E 01       GEE    =   2.1674E 01
                        F1     =  0.0              B1     =   0.0
                        DEG1   =  1.3078E-01       FEB    =   1.4313E 00
                        XPB    =  1.5173E 00       YPB    =   9.6000E 01
                        XTS    =  8.4527E-02       YTS    =   9.6000E 01
                        XBS    =  2.8995E-01       YBS    =   6.0001E 00

                        VEC    =  1.2127E 01       CDELC  =   1.4059E 01
                        F2     =  0.0              B2     =   0.0
                        DEG2   =  1.2271E-01       FES    =  -8.2447E-02
                        X2     =  1.1768E 00       Y2     =   2.5500E 02
                        X1     =  1.8724E-01       Y1     =   5.1000E 01
```

MINIMUM 0.0 — GEE VERSUS TIME — MAXIMUM 2.2102E 01

TIME	GEE	I ... I	XC	VEC
0.0	0.0	+	0.0	1.9953E 01
3.0000E-03	1.6154E 00	---+	1.0554E 00	1.9920E 01
6.0000E-03	3.1810E 00	-------+	2.1070E 00	1.9814E 01
9.0000E-03	4.7031E 00	----------+	3.1513E 00	1.9642E 01
1.2000E-02	6.2110E 00	--------------+	4.1847E 00	1.9403E 01
1.5000E-02	7.7019E 00	-----------------+	5.2037E 00	1.9098E 01
1.8000E-02	9.1593E 00	--------------------+	6.2049E 00	1.8729E 01
2.1000E-02	1.0598E 01	-----------------------+	7.1849E 00	1.8296E 01
2.4000E-02	1.2037E 01	---------------------------+	8.1403E 00	1.7801E 01
2.7000E-02	1.3448E 01	------------------------------+	9.0678E 00	1.7243E 01
3.0000E-02	1.4774E 01	---------------------------------+	9.9642E 00	1.6625E 01
3.3000E-02	1.6002E 01	------------------------------------+	1.0826E 01	1.5951E 01
3.6000E-02	1.7170E 01	--------------------------------------+	1.1652E 01	1.5225E 01
3.9000E-02	1.8299E 01	---+	1.2437E 01	1.4449E 01
4.2000E-02	1.9438E 01	---+	1.3180E 01	1.3623E 01
4.5000E-02	2.0708E 01	--+	1.3878E 01	1.2746E 01
4.8000E-02	2.1974E 01	---+	1.4528E 01	1.1808E 01
5.1000E-02	0.0	+	1.5137E 01	1.1438E 01
5.4000E-02	0.0	+	1.5742E 01	1.1438E 01
5.7000E-02	0.0	+	1.6347E 01	1.1438E 01
6.0000E-02	0.0	+	1.6953E 01	1.1438E 01
6.3000E-02	0.0	+	1.7558E 01	1.1438E 01
			1.9163E 01	1.1438E 01

APPENDIX C

HIGH-SPEED FILM ANALYSES

of

PENDULUM TESTS

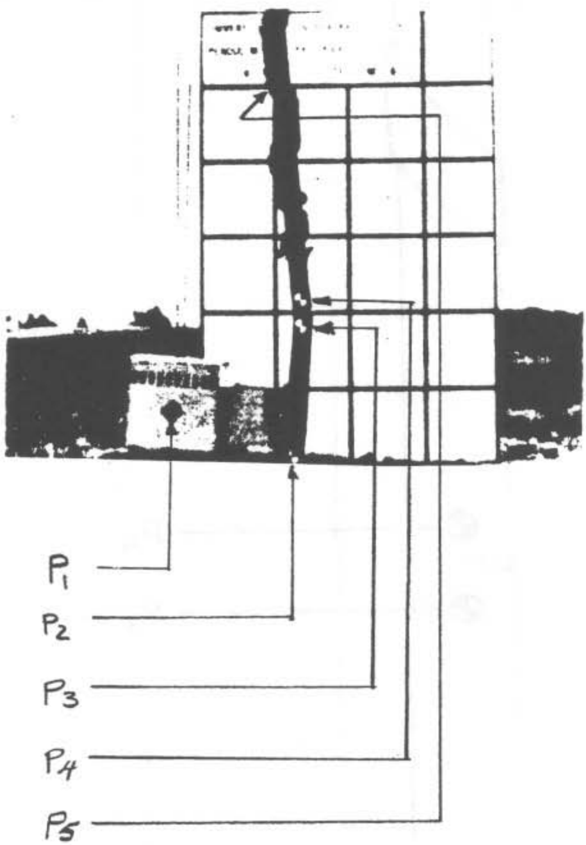
of

25 ft. BREAKAWAY UTILITY POLES

(TEST NO. 7)

High-speed film analyses

Pendulum Utility Pole Test No. 7



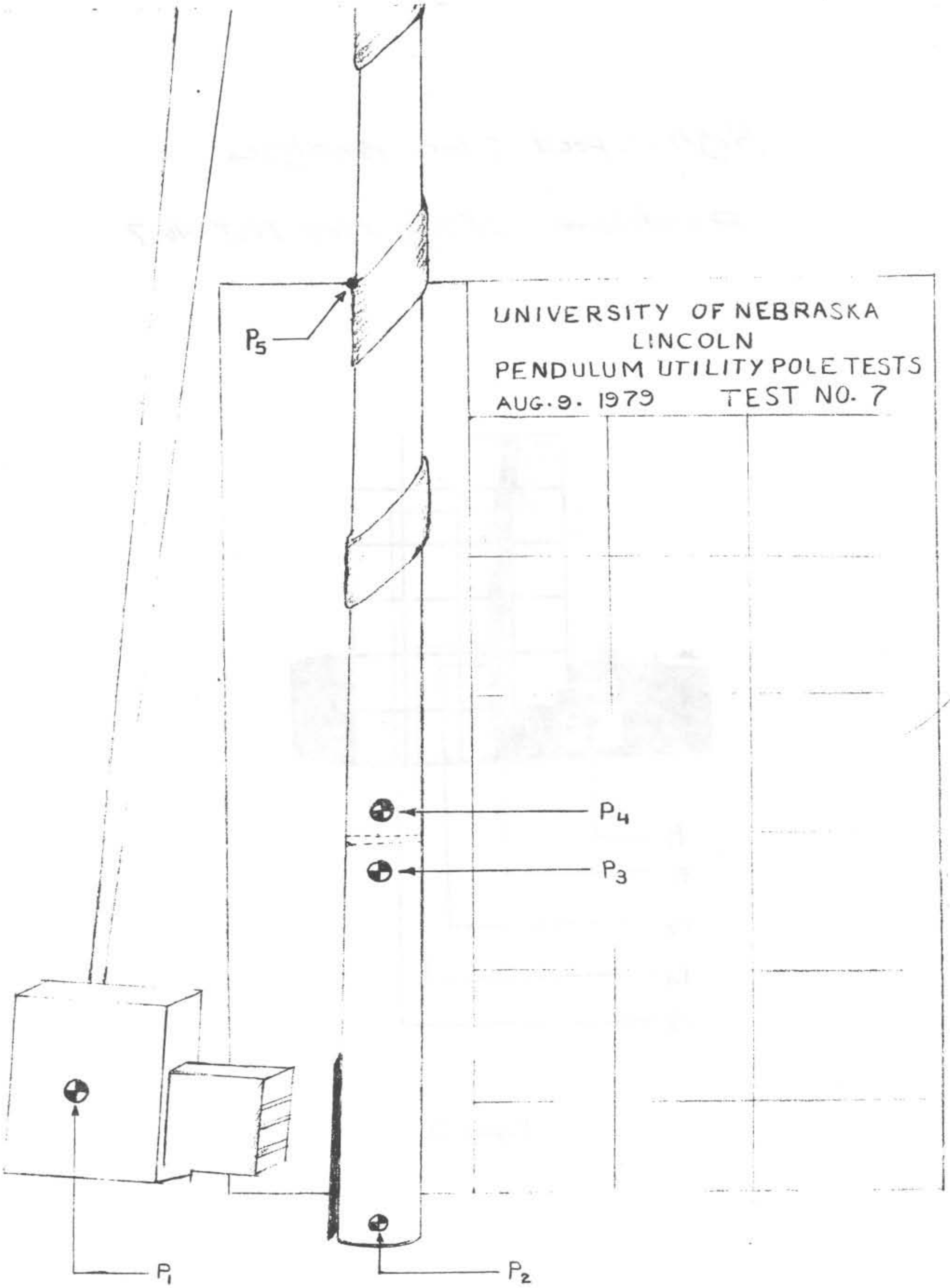

UNIVERSITY OF NEBRASKA
LINCOLN
PENDULUM UTILITY POLE TESTS
AUG. 9. 1979
TEST NO. 7
P5
P4
P3
P1
P2

Figure C2

P_1 Initial velocity = 14.93 ft/sec.

T (sec)	X_1 (inch)	Y_1 (inch)	X_2 (inch)	Y_2 (inch)	X_3 (inch)	Y_3 (inch)	X_4 (inch)	Y_4 (inch)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.004	0.716	0.072	0.287	0.215	0.824	-0.143	0.860	-0.108
0.008	1.361	0.180	0.609	0.251	2.042	-0.286	1.935	-0.144
0.012	2.077	-0.071	1.075	0.394	3.152	-0.322	3.081	-0.180
0.016	2.973	0.144	1.612	0.179	4.406	-0.215	4.407	-0.108
0.020	3.546	0.180	2.042	0.394	5.767	-0.250	5.876	-0.252
0.024	4.334	0.073	2.615	0.394	7.164	-0.107	7.344	-0.216
0.028	4.800	0.109	3.188	0.394	8.454	-0.143	8.454	-0.395
0.032	5.588	0.109	4.048	0.251	9.886	0.072	9.637	-0.252
0.036	6.448	0.037	4.944	0.000	11.211	0.323	10.712	-0.288
0.040	6.878	0.288	5.768	0.215	12.035	0.144	11.536	-0.396
0.044	7.676	0.216	6.807	-0.251	13.002	0.574	12.396	-0.145
0.048	8.070	0.324	7.738	-0.262	13.969	0.717	13.291	-0.109
0.052	8.643	0.288	8.454	-0.584	14.829	1.004	13.864	0.177
0.056	9.109	0.181	9.135	-0.620	15.760	1.291	14.724	0.249
0.060	9.682	0.181	9.887	-0.799	16.763	1.506	15.476	0.392
0.064	10.148	0.181	10.425	-1.121	17.981	1.972	16.264	0.607
0.068	10.864	0.181	11.321	-1.130	19.199	2.402	17.303	0.679
0.072	11.545	0.109	12.252	-1.238	20.775	2.330	18.342	0.787
0.076	12.405	0.181	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
0.080	13.050	0.217						
0.084	13.731	0.360						
0.088	14.340	0.396						
0.092	14.913	0.396						
0.096	15.844	0.539						

Table C1

P₁

Δx (Inch)	Δy (Inch)	Δt (Sec.)	V_x (ft/Sec)	V_y (fT/sec)	a_x (fT/Sec²)	a_y (fT/Sec²)	R (Inch)	V_{Total} (fT/Sec)	a_{Total} (fT/Sec²)
1.8627	0.2866	0.01	15.52	2.39			1.885	15.71	
					150.0	-209.0			+131.0
2.0420	0.0358	0.01	17.02	0.30			2.042	17.02	
					-120.0	+149.0			-109.0
1.8985	0.2149	0.01	15.82	1.79			1.911	15.93	
					-89.0	5.0			-90.0
1.7910	0.2149	0.01	14.93	1.79			1.804	15.03	
					+268.0	-60.0			+262.0
2.1134	0.1433	0.01	17.61	1.19			2.118	17.65	
					-179.0	+0.4			-182.0
1.8985	0.1433	0.01	15.82	1.194			1.900	15.33	
					+60.0	+60.0			+60.0
1.9701	0.0716	0.01	16.42	0.60			1.971	16.43	
					-299.0	+164.0			-280.0
■ 0.6448	0.1075	0.004	13.43	2.24			0.654	13.63	
					+560.0	+372.5	0		+617.5
0.7522	0.1791	0.004	15.67	3.73			0.773	16.10	
					-185.0	-372.5			-255.0
0.7164	0.1075	0.004	14.93	2.24			0.724	15.08	
					+515.0	+82.5			+527.5
* 0.8156	0.1235	0.004	16.99	2.57			0.825	17.19	
					-515.0	-270.0			-547.5
0.7164	0.0716	0.004	14.93	1.49			0.720	15.0	
					-375.0	+187.5			-342.5
0.6448	0.1075	0.004	13.43	2.24			0.654	13.63	
					+375.0	+745.0			+545.0
0.7164	-0.2507	0.004	14.93	-5.22			0.759	15.81	
					+932.5	-185			+845.0
0.8955	0.2149	0.004	18.66	4.48			0.921	19.19	
					-1680.0	-932.5			-1807.5
0.5731	0.0358	0.004	11.94	0.75			0.574	11.96	
					+1120.0	+372.5			+1150.0
0.7881	-0.1075	0.004	16.42	-2.24			0.795	16.56	
					-1680	-372.5			-1707.5
0.4657	0.0358	0.004	9.70	0.75			0.467	9.73	
					+1680	-187.5			+1672.5
0.7881	0.0000	0.004	16.42	0.00			0.7881	16.42	
					+372.5	-372.5			+390.0
0.8597	-0.0716	0.004	17.91	-1.49			0.863	17.98	
					-2237.5	+932.5			-1900.0
0.4299	0.2507	0.004	8.96	5.22			0.498	10.38	
					+1920	-932.5			+1577.5
0.7985	-0.0716	0.004	16.64	7.47			0.801	16.69	
					-2107.5	+187.5			-2042.5
0.3940	0.1075	0.004	8.21	2.24			0.408	8.50	

* Point of Impact.

■ @ This Time data has been Taken for 5 Points.

Δx (inch)	Δy (inch)	Δt (sec)	V_x (ft/sec)	V_y (ft/sec)	a_x (ft/sec²)	a_y (ft/sec²)	R (inch)	V_{Total} (ft/sec)	a_{Total} (ft/sec²)
					+932.5	-372.5			
0.5731	-0.0358	0.004	11.94	-0.75			0.574	11.96	
					-560.0	+127.5			-500.0
0.4657	-0.1075	0.004	9.70	-0.24			0.478	9.96	
					+560.0	+60.0			+495.0
0.5731	0.0000	0.004	11.94	0.00			0.573	11.94	
					-560.0	0.0			-557.5
0.4657	0.0000	0.004	9.70	0.00			0.466	9.71	
					+1307.5	0.0			+1302.5
0.7164	0.0000	0.004	14.93	0.00			0.716	14.92	
					-187.5	+372.5			-167.5
0.6806	-0.0716	0.004	14.18	-1.49			0.684	14.25	
					+932.5	+745.0			+932.5
0.8597	0.0716	0.004	17.91	1.49			0.863	17.98	
					-1120.0	-185.0			-1130.0
0.6448	0.0358	0.004	13.43	0.75			0.646	13.46	
					+187.5	+560.0			+260.0
0.6806	0.1433	0.004	14.18	2.99			0.696	14.50	
					-372.5	-560.0			-447.5
0.6089	0.0358	0.004	12.69	0.75			0.610	12.71	
					-187.5	-187.5			-170.5
0.5731	0.0000	0.004	11.94	0.00			0.573	11.94	
					+1865.0	-747.5			+1922.5
0.9313	0.1433	0.004	19.40	2.99			0.942	19.63	
					-812.0	-418.0			-852.0
** 1.3254	-0.1433	0.01	11.28	-1.19			1.333	11.11	
					+126.0	+179.0			+144.0
1.5045	0.0716	0.01	12.54	0.60			1.506	12.55	
					+119.0	+179.0			+138.0
1.6478	0.2866	0.01	13.73	2.39			1.673	13.94	
					-179.0	-120.0			-198.0
1.4328	0.0716	0.01	11.94	1.19			1.435	11.96	
					+209.0	-89.0			+207.0
1.6836	0.0358	0.01	14.03	0.30			1.684	14.03	
					-90.0	+60.0			-86.0
1.5761	0.1075	0.01	13.13	0.90			1.580	13.17	
					+90.0	0.0			+89.0
1.6836	0.1075	0.01	14.03	0.90			1.687	14.06	

** change in Δt

P₂

Table C3

	Δx (Inch)	Δy (Inch)	Δt (Sec)	V_x (FT/sec)	V_y (FT/sec)	a_x (FT/sec²)	a_y (FT/sec²)	R (Inch)	V_{Total} (FT/sec)	a_{Total} (FT/sec²)
	0.2507	$\bar{0}$.1075	0.004	5.22	-2.24			0.273	5.69	
						-2610.	2800			1165
	-0.2507	0.4299	0.004	-5.22	8.96			0.497	10.35	
						1678	2240			-2713
	0.0716	0.0000	0.004	1.49	0.00			0.072	1.50	
						2800.	560			2840
*	0.6090	0.1075	0.004	12.69	2.24			0.618	12.86	
						-1680.	560			-1350
	0.2866	0.2149	0.004	5.97	4.48			0.358	7.46	
						188.0	-933			-1533
	0.3224	0.0358	0.004	6.72	0.75			0.323	6.73	
						745.0	560			855
	0.4657	0.1433	0.004	9.70	2.99			0.487	10.15	
						373.0	-1868			478
	0.5373	-0.2149	0.004	11.19	-4.48			0.579	12.06	
						-558	2240			-510
	0.4299	0.2149	0.004	8.96	4.48			0.481	10.02	
						745.	-1120			480
	0.5731	0.0000	0.004	11.94	0.00			0.573	11.94	
						0.0	0.0			0.0
	0.5731	0.0000	0.004	11.94	0.00			0.573	11.94	
						1493.	-748			1558
	0.8597	$\bar{0}$.1433	0.004	17.91	-2.99			0.872	18.17	
						188.0	-558			303
	0.8956	$\bar{0}$.2507	0.004	18.66	-5.22			0.930	19.38	
						-375	2425			-413
	0.8239	0.2149	0.004	17.16	4.48			0.851	17.73	
						1120.	-3545			1495
	1.0388	$\bar{0}$.4657	0.004	21.64	-9.70			1.138	23.71	
						-560	2238			-1073
	0.9313	$\bar{0}$.0358	0.004	19.40	-0.75			0.932	19.42	
						560	130.0			558
	1.0388	$\bar{0}$.0110	0.004	21.64	-0.23			1.039	21.65	
						-1678	-1623			-1318
	0.7164	$\bar{0}$.3224	0.004	14.93	-6.72			0.786	16.38	
						-188	1493			-543
	0.6806	$\bar{0}$.0358	0.004	14.18	-0.75			0.682	14.21	
						373	-745			473
	0.7522	$\bar{0}$.1791	0.004	15.67	-3.73			0.773	16.10	
						-1120	-745			-760
	0.5373	$\bar{0}$.3223	0.004	11.19	-6.71			0.627	13.06	
						1868	1630			1403
	0.8955	$\bar{0}$.009	0.004	18.66	-0.19			0.896	18.67	
						185.	-513.0			213
	0.9313	$\bar{0}$.1075	0.004	19.40	-2.24			0.937	19.52	

Table C4

Δx (inch)	Δy (inch)	Δt (sec)	V_x (ft/sec)	V_y (ft/sec)	a_x (ft/sec²)	a_y (ft/sec²)	R (inch)	V_{Total} (ft/sec)	a_{Total} (ft/sec²)
0.0358	0.0000	0.004	0.746	0.000			0.036	0.8	
					0.0	0.0			0.0
0.0358	0.0000	0.004	0.746	0.000			0.036	0.8	
					374	0.0			375
0.1075	0.0000	0.004	2.240	0.000			0.108	2.3	
					4478	-190			4475
0.9672	$\bar{0}$.0358	0.004	20.15	$\bar{0}$.76			0.968	20.2	
					-748	-558			-700
0.8239	$\bar{0}$.1433	0.004	17.16	$\bar{2}$.99			0.836	17.4	
					2053	0.0			2025
1.2179	$\bar{0}$.1433	0.004	25.37	-2.99			1.226	25.5	
					-560	558			-600
1.1104	$\bar{0}$.0358	0.004	23.13	-0.76			1.11	23.1	
					748	750			800
1.2537	0.1075	0.004	26.12	2.24			1.26	26.3	
					560	-750			500
1.3612	$\bar{0}$.0358	0.004	28.36	-0.76			1.36	28.3	
					185	938			225
1.3970	0.1433	0.004	29.10	2.99			1.40	29.2	
					-558	-938			-575
1.2896	$\bar{0}$.0358	0.004	26.87	-0.76			1.29	26.9	
					745	1310			825
1.4328	0.2149	0.004	29.85	4.48			1.45	30.2	
					-560	185			-525
1.3254	0.2507	0.004	27.61	5.22			1.35	28.1	
					-2613	-2238			-2650
0.8239	$\bar{0}$.1791	0.004	17.16	$\bar{3}$.73			0.84	17.5	
					748	3173			1150
0.9672	0.4299	0.004	20.15	8.96			1.06	22.1	
					0.0	-1493			-425
0.9672	0.1433	0.004	20.15	2.99			0.98	20.4	
					-560	745			-350
0.8597	0.2866	0.004	17.91	5.97			0.91	19.0	
					373	0.0			300
0.9313	0.2866	0.004	19.40	5.97			0.97	20.2	
					375	-373			425
1.0030	0.2149	0.004	20.90	4.48			1.05	21.9	
					1118	1305			1300
1.2179	0.4657	0.004	25.37	9.70			1.30	27.1	
					0.0	-185			-50
1.2179	0.4299	0.004	25.37	8.96			1.29	26.9	
					1873	2613			1500
1.5761	$\bar{0}$.0716	0.004	32.86	$\bar{1}$.49			1.58	32.9	

Γ_4

Table C5

Δx (inch)	Δy (inch)	Δt (Sec)	V_x (ft/sec)	V_y (ft/sec)	a_x (ft/sec²)	a_y (ft/sec²)	R (inch)	V_{Total} (ft/sec)	a_{Total} (ft/sec²)
0.0358	0.0358	0.004	0.7	0.7			0.051	1.1	
					0.0	750			675
0.0358	0.1791	0.004	0.7	3.7			0.183	3.8	
					200	-550			-425
0.0716	0.0716	0.004	1.5	1.5			0.101	2.1	
					4475	550			4425
0.9313	$\bar{0}.1791$	0.004	19.4	3.7			0.948	19.8	
					-375	-375			-2450
0.8597	$\bar{0}.1075$	0.004	17.9	2.2			0.866	10.0	
					1125	-375			3100
1.0746	$\bar{0}.0358$	0.004	22.4	0.7			1.075	22.4	
					375	0.0			375
1.1463	$\bar{0}.0358$	0.004	23.9	0.7			1.147	23.9	
					925	200			925
1.3254	0.0716	0.004	27.6	1.5			1.327	27.6	
					750	375			800
1.4687	$\bar{0}.1433$	0.004	30.6	3.0			1.476	30.8	
					0.0	-575			-50
1.4687	0.0358	0.004	30.6	0.7			1.469	30.6	
					-1875	750			-1800
1.1104	$\bar{0}.1791$	0.004	23.1	3.7			1.125	23.4	
					375	-175			350
1.1821	0.1433	0.004	24.6	3.0			1.191	24.8	
					-550	-575			-600
1.0746	0.0358	0.004	22.4	0.7			1.075	22.4	
					-1300	375			-1275
0.8239	$\bar{0}.1075$	0.004	17.2	2.2			0.831	17.3	
					175	750			350
0.8597	0.2507	0.004	17.9	5.2			0.896	18.7	
					200	-1125			0.0
0.8955	0.0358	0.004	18.7	0.7			0.896	18.7	
					-1700	1325			-1325
0.5731	0.2866	0.004	11.9	6.0			0.641	13.4	
					1500	225			1150
0.8597	0.0716	0.004	17.9	1.5			0.863	18.0	
					-550	375			-500
0.7522	0.1433	0.004	15.7	3.0			0.766	16.0	
					175	375			250
0.7881	0.2149	0.004	16.4	4.5			0.817	17.0	
					1300	-750			1175
1.0388	0.0716	0.004	21.6	1.5			1.041	21.7	
					0.0	175			25
1.0388	0.1075	0.004	21.6	2.2			1.044	21.8	

Δx (inch)	Δy (inch)	Δt (sec)	V_x (ft/sec)	V_y (ft/sec)	a_x (ft/sec²)	a_y (ft/sec²)	R (inch)	V_{Total} (ft/sec)	a_{Total} (ft/sec²)
0.0000	0.0358	0.004	0.0	0.75			0.036	0.75	
					0.0	1305			1308
0.0000	0.2866	0.004	0.0	5.97			0.287	5.98	
					188	-933			-933
0.0358	$\bar{0}.1075$	0.004	0.75	2.24			0.108	2.25	
					1493	188			1275
0.3224	$\bar{0}.1433$	0.004	6.72	2.99			0.353	7.35	
					-748	-375			-833
$\bar{0}.1791$	0.0716	0.004	3.73	1.49			0.193	4.02	
					373	933			418
$\bar{0}.2507$	0.1075	0.004	5.22	5.22			0.273	5.69	
					-745	-745			-630
0.1075	$\bar{0}.1075$	0.004	2.24	2.24			0.152	3.17	
					933	933			703
0.2866	$\bar{0}.0358$	0.004	5.97	5.97			0.287	5.98	
					560	560			558
0.3940	$\bar{0}.0358$	0.004	8.21	8.21			0.394	8.21	
					-1120	-1305			-860
0.1791	$\bar{0}.1433$	0.004	3.73	2.99			0.229	4.77	
					1308	933			1605
0.4299	0.3224	0.004	8.96	6.72			0.537	11.19	
					0.0	185			120
0.4299	$\bar{0}.3582$	0.004	8.96	7.46			0.560	11.67	
					2050	-1305			1410
0.8239	0.1075	0.004	17.16	2.24			0.831	17.31	
					-933	560			-968
0.6448	0.0000	0.004	13.43	0.00			0.645	13.44	
					2425	2053			2775
1.1104	$\bar{0}.3940$	0.004	23.13	8.21			1.178	24.54	
					188	-1305			-120
1.1463	$\bar{0}.1433$	0.004	23.88	2.99			1.155	24.06	
					-3173	-188			-3160
0.5373	0.1075	0.004	11.19	2.24			0.548	11.42	
					2800	188			2790
1.0746	$\bar{0}.1433$	0.004	22.39	2.99			1.084	22.58	
					-2425	-375			-2453
0.6090	$\bar{0}.0716$	0.004	12.69	1.49			0.613	12.77	
					-2240	1120			-1433
0.1791	$\bar{0}.2866$	0.004	3.73	5.97			0.338	7.04	
					2425	-1120			1620
0.6448	$\bar{0}.0716$	0.004	13.43	1.49			0.649	13.52	
					2985	-185			2965
1.2179	0.0358	0.004	25.37	0.75			1.218	25.38	

APPENDIX D

HIGH-SPEED FILM ANALYSES

of

FULL-SCALE VEHICLE CRASH TEST

of

40 ft CLASS 4 BREAKAWAY UTILITY POLE

High - speed film analyses

Full- scale Test No. 1.

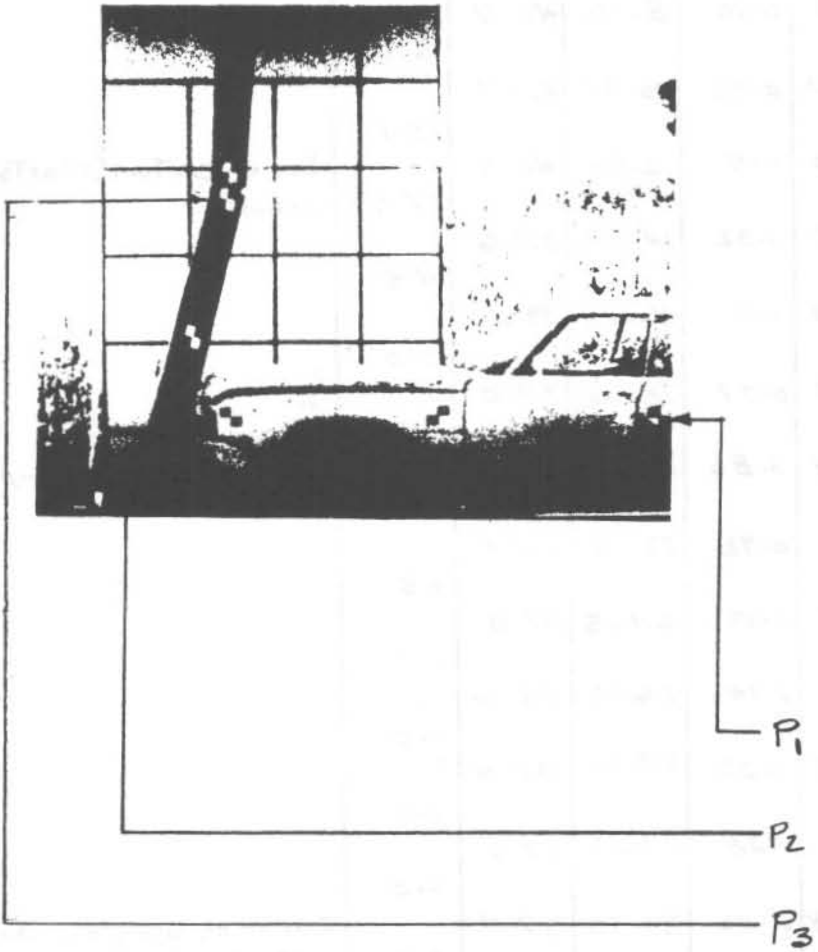


Figure D1

TABLE D1

CRITICAL EVENTS

$V_I = 30.8$ MPH & $V_F = 25.1$ MPH.

T (sec)	X_1 (Inch)	Y_1 (Inch)	R (Inch)	V (FT/sec)	G's	Critical Events, Comments
0.0000	0.00	0.00	0.00	45.6		Assumed Impact Time.
					2.3	
0.0041	2.22	0.21	2.23	45.3	—	Car starting To crush
					4.5	
0.0083	4.41	0.38	4.43	44.7		pole has deflection in upper section.
					6.1	
0.0124	6.57	0.52	6.59	43.9		
					1.5	
0.0166	8.73	0.70	8.76	43.7		
					6.1	
0.0207	10.83	0.92	10.87	42.9		
					15.1	
0.0248	12.83	1.15	12.88	40.9		Lower Section starts To move
					17.4	rapidly.
0.0290	14.72	1.32	14.78	38.6		
					4.5	
0.0331	16.64	1.12	16.71	39.2		
					3.0	
0.0373	18.54	0.97	18.62	38.8		←
					1.5	
0.0414	20.44	0.86	20.52	38.6		Lower Joint completly severed.
					4.5	
0.0455	22.31	0.92	22.39	38.0		
					1.5	
0.0497	24.17	0.99	24.25	37.8		
					1.5	
0.0538	26.01	1.14	26.10	37.6	—	
					1.5	
0.0580	27.87	1.23	27.96	37.8		
					1.5	
0.0621	29.72	1.28	29.81	37.6		
					0.3	
0.0828	38.94	2.00	39.10	37.4		Car has been crushed 1.5FT ± 3"
					0.5	UP To This Point.
0.1035	48.16	1.98	48.32	37.1		Upper Joint Failed Completely
					0.5	
0.1241	57.31	2.42	57.48	36.9		
					0.2	
0.1449	66.5	2.64	66.67	36.8		

TABLE D2

T (sec)	X_2 (inch)	Y_2 (inch)	R (inch)	V (ft/sec)	a (ft/sec^2)
0.000	0.00	0.00	0.00	0.00	0.0
					7.8
0.0103	0.01	0.0	0.01	0.08	
					2349
0.0207	2.99	0.340	3.01	24.27	
					1546
0.0311	7.923	0.985	7.98	40.21	
					188.3
0.0414	13.058	1.836	13.19	42.15	
					1555
0.0517	20.213	2.585	20.38	58.17	
					141.7
0.0621	27.55	3.27	27.75	59.63	
					23.3
0.0725	34.83	4.59	35.15	59.87	
					0.0
0.0828	42.11	5.92	42.55	59.87	
					-612.6
0.0931	48.50	7.65	49.17	53.56	
					7.8
0.1035	54.90	9.39	55.80	53.64	
					-72.9
0.1242	66.53	14.49	68.50	52.13	
					127
0.1449	79.86	17.07	82.10	54.75	
					319
0.1656	95.10	N.A.	97.34	61.35	
					N.A.
0.1863	N.A	N.A.	N.A.	N.A.	

TABLE D3

T (sec)	X_3 (inch)	Y_3 (inch)	R (inch)	V (FT/sec)	a (FT/sec²)
0.00	0.00	0.00	0.00	0.00	0.00
					903
0.0103	1.130	$\bar{0}.223$	1.15	9.3	
					146
0.0207	2.449	$\bar{0}.408$	2.48	10.8	
					544
0.0311	4.462	$\bar{0}.121$	4.51	16.4	
					728
0.0414	7.415	0.204	7.46	23.9	
					$\bar{7}94$
0.0517	10.120	0.172	10.17	21.9	
					$\bar{2}9.1$
0.0621	12.789	0.136	12.84	21.6	
					$\bar{3}49.5$
0.0725	15.012	0.334	15.10	18.3	
					$\bar{3}8.8$
0.0828	17.211	0.544	17.31	17.9	
					680
0.0931	20.28	0.340	20.39	24.9	
					$\bar{9}.71$
0.1035	23.33	0.136	23.46	24.8	
					$\bar{4}83.$
0.1242	27.01	$\bar{0}.272$	27.14	14.8	
					560.
0.1449	33.54	$\bar{0}.884$	33.70	26.4	
					$\bar{9}2.$
0.1656	39.52	$\bar{1}.972$	39.78	24.5	
					$\bar{6}04.$
0.1863	42.38	$\bar{2}.79$	42.76	12.0	

HIGH-SPEED FILM ANALYSIS

FULL SCALE TEST NO.2

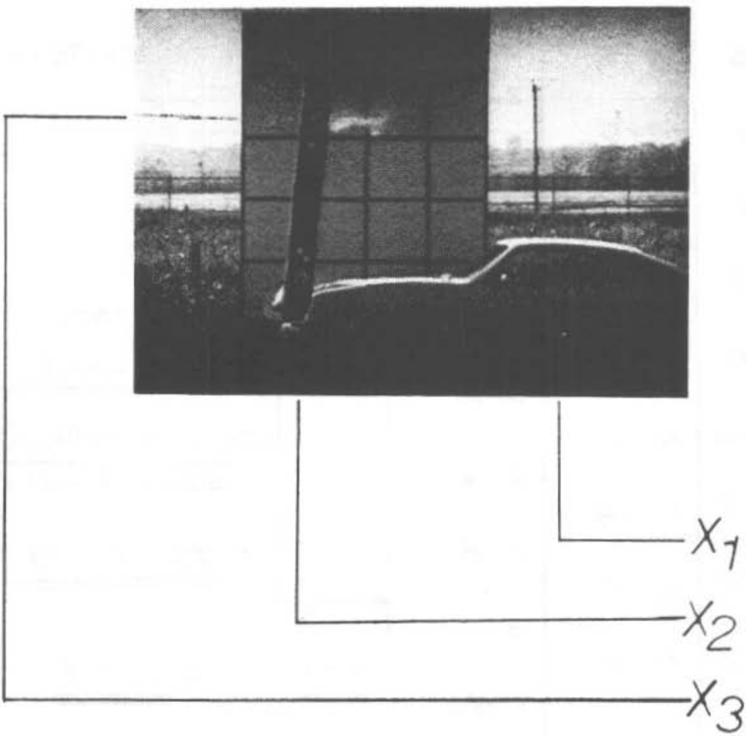


TABLE D4 CRITICAL EVENTS

$V_I = 21.4$ MPH & $V_F = 9.4$ MPH

T (sec)	X (inch)	V (FT/sec)	G's	Critical Events, Comments
0.0068	2.31	28.3		
			0.0	
0.0136	4.62	28.3		
			1.8	Deflection in upper joint.
0.0204	6.90	27.9		
			6.4	Upper joint moving rapidly.
0.0272	9.06	26.5		
			1.8	
0.0340	11.19	26.1		
			0.9	
0.0408	13.30	25.9		
			3.7	
0.0476	15.35	25.1		
			2.7	
0.0544	17.35	24.5		Lower joint starts moving
			22.8	
0.0612	18.94	19.5		
			21.5	
0.0680	20.15	14.8		
			3.2	
0.0748	21.30	14.1		
			2.3	54.4 msec
0.0816	22.41	13.6		Peak Momentum =
			3.2	
0.0884	23.46	12.9		$\frac{(24.5-12.0)\,\text{ft/sec}\,(2450\,\text{lb})}{32.2\ \text{lb}_m\,\text{ft/sec}^2\,\text{lb}_f}$
			2.3	
0.0952	24.47	12.4		
			1.8	= 951.1 lbf sec
0.1020	25.45	12.0		
			3.2	
0.1088	26.37	11.3		Peak G = 22.8
			1.4	
0.1156	27.27	11.0		
			0.5	Average G over 54.4 msec
0.1224	28.16	10.9		= 7.4
			0.0	
0.1292	29.05	10.9		
			5.5	
0.1360	29.84	9.7		
			1.4	
0.1428	30.61	9.4		
			0.0	
0.1496	31.38	9.4		

TABLE D5

Time (Sec)	X_2 (Inch)	X_3 (Inch)	V_2 (FT/sec)	V_3 (FT/sec)	a_2 (FT/sec^2)	a_3 (FT/sec^2)
0.0068	0.20	0.09	2.45	1.10		
					0.0	360.3
0.0136	0.40	0.38	2.45	3.55		
					360.3	307.4
0.0204	0.80	0.84	4.90	5.64		
					270.6	360.3
0.0272	1.35	1.50	6.74	8.09		
					$\bar{5}4.4$	107.4
0.0340	1.87	2.22	6.37	8.82		
					19.1	19.11
0.0408	2.40	2.95	6.50	8.95		
					35.3	35.3
0.0476	2.95	3.70	6.74	9.19		
					$\bar{5}4.4$	$\bar{7}20.6$
0.0544	3.47	4.05	6.37	4.29		
					307.4	360.3
0.0612	4.16	4.60	8.46	6.74		
					216.2	305.9
0.0680	4.97	5.32	9.93	8.82		
					827.9	307.4
0.0748	6.24	6.21	15.56	10.91		
					$\bar{4}67.6$	0.0
0.0816	7.25	7.10	12.38	10.91		
					666.2	216.2
0.0884	8.63	8.11	16.91	12.38		
					$\bar{7}98.5$	77.9
0.0952	9.90	9.18	15.56	13.11		
					$\bar{3}60.3$	0.0
0.1020	10.97	10.25	13.11	13.11		
					883.8	144.11
0.1088	12.53	11.40	19.12	14.09		
					$\bar{6}30.9$	$\bar{4}67.6$
0.1156	13.74	12.29	14.83	10.91		
					0.0	414.7
0.1224	14.95	13.41	14.83	13.73		
					$\bar{2}52.9$	$\bar{3}07.4$
0.1292	16.02	14.36	13.11	11.64		
					414.7	0.0
0.1360	17.32	15.31	15.93	11.64		
					$\bar{7}61.8$	163.2
0.1428	18.53	16.35	14.83	12.75		

HIGH SPEED FILM ANALYSIS
FULL-SCALE TEST NO.3

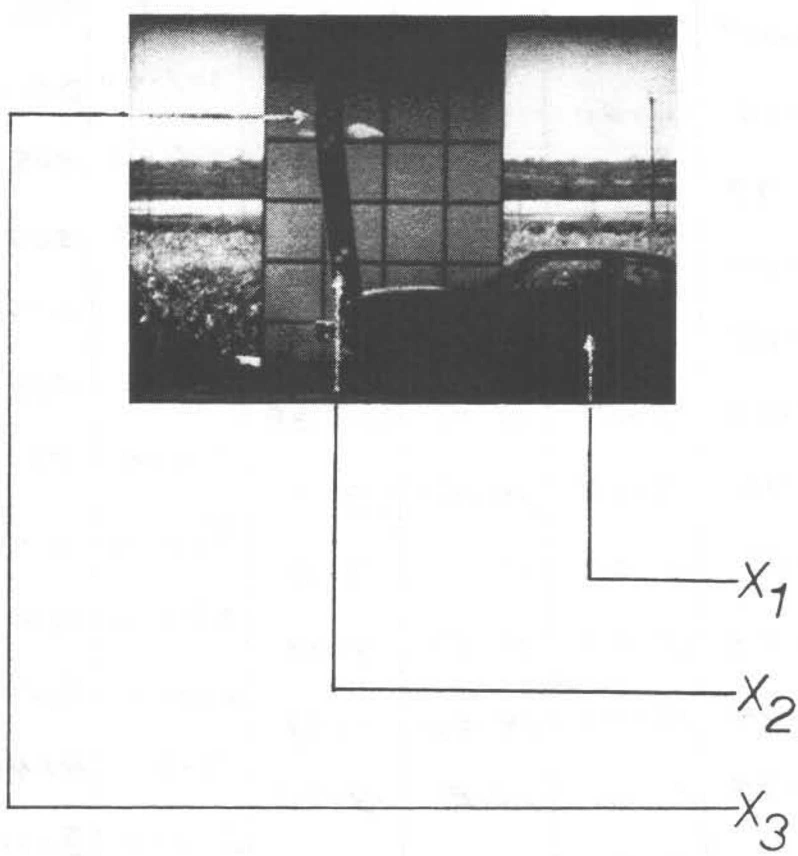


Figure D3

TABLE D6 CRITICAL EVENTS

$V_I = 20.77$ MPH & $V_F = 6.2$ MPH

T(sec)	X (Inch)	V(FT/sec)	G's	Critical Events . Comments
0.00535	1.90	29.6		
			12.9	
0.00107	3.66	27.4		Deflection in upper Joint.
			2.9	
0.01605	5.39	26.9		
			1.8	
0.0214	7.18	26.6		increase in Deflection in upper Joint.
			7.0	
0.02675	8.73	25.4		
			8.2	
0.0321	10.27	24.0		
			-1.8	
0.03745	11.83	24.3		
			14.6	lower Joint starts moving.
0.0428	13.23	21.8		
			0.0	
0.04815	14.52	21.8		
			1.8	
0.0535	15.90	21.5		
			2.9	
0.0589	17.25	21.0		← (start of 48 m sec interval)
			11.7	
0.0642	18.47	19.0		
			-5.3	
0.0696	19.75	19.9		
			1.8	
0.0749	21.01	19.6		
			8.2	
0.0803	22.18	18.2		48 m sec.
			12.9	Peak Momentum:
0.0856	23.21	16.0		$\frac{(21.0-7.3)\ \text{FT/sec}\ (2450\ \text{lb})}{32.2\ \text{lb}_m\text{FT/sec}^2\ \text{lb}_f}$
			9.9	
0.07095	24.13	14.3		
			19.9	$= 1042.4\ \text{lb}_f\ \text{sec}$
0.0963	24.83	10.9		
			13.4	
0.10170	25.38	8.6		Averag G over 48 m sec
			7.6	
0.1070	25.85	7.3		← (end of 48 m sec interval) = 8.9
			6.4	
0.1124	26.25	6.2		

TABLE D7

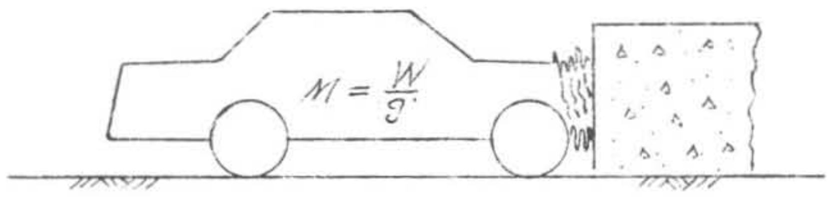
Time (Sec)	X_2 (Inch)	X_3 (Inch)	V_2 (FT/Sec)	V_3 (FT/Sec)	a_2 (FT/Sec^2)	a_3 (FT/Sec^2)
0.00535	0.31	0.04	4.8	0.6		
					150.0	935.0
0.00107	0.67	0.40	5.6	5.6		
					150.0	1047.0
0.01605	0.98	0.40	4.8	0.0		
					411.0	1458.0
0.0214	1.15	0.90	2.6	7.8		
					2841.0	1176.0
0.02675	2.29	1.99	17.8	1.4		
					2112.0	1607.0
0.0321	2.71	1.63	6.5	10.0		
					393.0	411.0
0.03745	2.99	2.13	4.4	7.8		
					486.0	467.0
0.0428	3.44	2.79	7.0	10.3		
					1458.0	206.0
0.04815	4.39	3.38	14.8	9.2		
					1047.0	318.0
0.0535	4.98	4.08	9.2	10.9		
					1720.0	523.0
0.0589	4.98	4.60	0.0	8.1		
					2262.0	2245.0
0.0642	5.76	5.89	12.1	20.1		
					131.0	1880.0
0.0696	6.49	6.53	11.4	10.0		
					93.0	785.0
0.0749	7.19	7.44	10.9	14.2		
					561.0	523.0
0.0803	8.08	8.53	13.9	17.0		
					1047.0	991.0
0.0856	8.61	9.28	8.3	11.7		
					636.0	1159.0
0.09095	9.36	10.43	11.7	17.9		
					804.0	37.0
0.0963	10.39	11.59	16.0	18.1		
					486.0	224.0
0.10170	11.25	12.70	13.4	17.3		
					467.0	206.0
0.1070	11.95	13.74	10.9	16.2		
					299.0	112.0
0.1124	12.75	14.74	12.5	15.6		

APPENDIX E

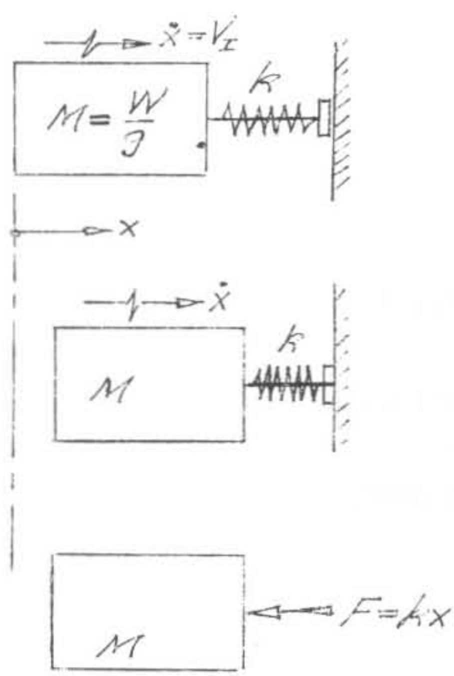
VEHICLE IMPACT MODEL
for
NON-YIELDING BARRIERS

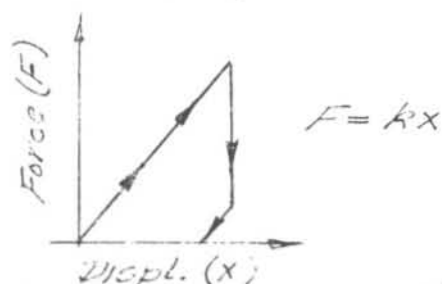
NON - YIELDING BARRIER

[after Emori (10)]



IDEALIZATION of VEHICLE IMPACT (Single D.O.F.)





Standard Size Vehicle

1. Wide Barrier ---- $k\left(\frac{lb}{ft}\right) = 12.5W$
2. Poles, Trees ---- $k\left(\frac{lb}{ft}\right) = 10.0W$

where: $\dot{x} = \frac{dx}{dt}$ and $\ddot{x} = \frac{d^2x}{dt^2}$

$$\overset{+}{\rightarrow}\ \Sigma F = Ma = M\ddot{x} = -kx$$

$M\ddot{x} + kx = 0$ — Linear Homogeneous 2nd Order Differential Equation (D.E.)

$\ddot{x} + \omega^2 x = 0$ — where: $\omega^2 = \frac{k}{M} = \frac{k}{(W/g)}$

General Solution to D.E.

$$x = A_1 \sin \omega t + A_2 \cos \omega t$$

Boundary Conditions

$$t = 0\ ;\ x = 0 \text{ and } \dot{x} = V_I$$

APPENDIX F

ORIGINAL DAMAGE ESTIMATES

ON FULL-SCALE TEST VEHICLES

Damage Report

145 614133

Name Uni Mehr. Date 11-27-79

Address ______ State ______ Zip ______ Phone ______

Year 74 Make Chev Model Vega I.D. No. ______

Color White Prod. Date ______ Trim ______ Mileage ______ License No. ______

Test Vehicle #2 File No. ______ Claim No. ______

	Description	Parts	Labor
X	Front bumper Ally face bar	127 00	24 00
X	Front bumper protect strip	42 00	Inc
X	Front bumper brkt sprigs assy	60 60	Inc
V	Front Valance	24 95	6 00
X	Grille	55 25	9 00
X	Front bumper filler	14 75	3 00
X	Header Panel	52 50	15 00
X	Radiator W/O air cond	98 00	15 00
X	Fan guard	3 10	Inc
X	Radiator support	73 25	52 50
X	Battery	47 95	3 00
X	Oil Pan	37 00	30 00
X	oil gaskets	8 95	Inc
	antifreeze	7 50	Inc
X	Front unitized frame section		
	+ align wheels		136 00
X	Right frt fender		15 00
X	Left frt fender		15 00
X	Hood	121 00	12 00
X	Hood latche	15 10	4 50
	Material + Paint	50 00	
	Paint as needed		105 00
	TOTALS	838 90	445 00

Authorization for Repair

PARTS Prices subject to invoice	$ 883.90
LABOR ___ hrs. @ $ ___	$ 445 00
Paint	$
Paint Supplies	$
Shop Supplies	$
Towing / Storage	$
Sublet	$
Tax	$ 35.36
DAMAGE REPORT TOTAL	$ 1364.26
CHANGES (See Back ✱)	$
NEW TOTAL	$

PETE'S BODY SHOP

2035 Yolande Street

Lincoln, Nebraska 68504

Damage Report

146 614099

Name: University of Nebr. Date: 11-27-79
Address: Civil Eng. Dept State: ___ Zip: ___ Phone: ___
Year: 74 Make: Vega Model: Orange I.D. No.: ___
Color: ___ Prod. Date: ___ Trim: ___ Mileage: ___ License No.: ___
Ins. Co.: Test Vehicle #3 File No.: ___ Claim No.: ___
Appraiser: ___ Tel. No.: ___ Phone: ___ Written By: ___

		Description	Parts	Labor
	X	frt bumper face bar all.	127 00	24 00
	X	frt bumper protective strip	42 00	incl
	X	frt bumper brackets spring		
	X	~~frt valance~~ assemblies	60 00	incl
	X	frt valance	24 95	6 00
	X	grille	55 25	9 00
	X	center frt bumper filler	14 75	3 00
	X	header panel	52 50	15 00
	X	Radiator W. air cond	118 00	15 00
	X	air cond condenser	121 95	15 00
	X	shroud	20 00	incl
	X	Replace Rad support	73 25	52 50
	X	Replace Battery	47 95	3 00
	X	Freon + service air	16 00	15 00
		antifreeze	9 00	incl
	X	rebuilt Alternator	47 50	7 50
X		Repair frt unitized frame & align wheels		136 00
X		R frt fender		30 00
X		left frt fender		30 00
	X	hood	121 00	12 00
	X	rear hood lower latch	15 10	4 50
		Paint & shop material	50 00	
		Paint as needed		120 00
		TOTALS	966 80	

Authorization for Repair

PARTS Prices subject to invoice	$ 966.80
LABOR ___ Hrs. @ $ ___	$ 497.50
Paint	$
Paint Supplies	$ 50.00
Shop Supplies	$
Towing / Storage	$
Sublet	$
Tax	$ 40.67
DAMAGE REPORT TOTAL	$ 1554.97
CHANGES (See Back *)	$
NEW TOTAL	$

PETE'S BODY SHOP

2035 Yolande Street
Lincoln, Nebraska 68504

With used Parts
$1154.97