NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 150

EFFECT OF CURB GEOMETRY AND LOCATION ON VEHICLE BEHAVIOR

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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EFFECT OF CURB GEOMETRY AND LOCATION ON VEHICLE BEHAVIOR

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AREAS OF INTEREST:

HIGHWAY DESIGN
HIGHWAY SAFETY

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report is recommended to highway administrators, design engineers, and others who have responsibility for establishing policy with respect to safety in the geometric design of highways. The research described was concerned specifically with the safety aspects of curb design. Full-scale tests in combination with computer simulations were applied to investigate vehicle behavior upon impact with a series of commonly used curbs. The results provide a basis for judgment on the selection of locations where curbs can be used for safety, and can be employed also in selecting designs where curb use seems appropriate.

According to the AASHTO publication *A Policy on Geometric Design of Rural Highways* (1965), curbs are used to control drainage, prevent vehicles from leaving the pavement at hazardous points, delineate the edge of the pavement, present a more finished appearance, and assist in the orderly development of the roadside. The research to which this report pertains was concerned with the important safety aspect of curb use, about which little factual information has been available.

Three commonly used curb types, two 6 in. and one 4 in. high, and a special configuration 13 in. high were investigated through the use of the Highway Vehicle Object Simulation Model (HVOSM) previously developed at the Cornell Aeronautical Laboratory (now Calspan), Buffalo, N.Y. The applicability of the model was evaluated by 18 full-scale tests on the two 6-in.-high curbs. A series of nine tests at vehicle speeds of 30, 45, and 60 mph, and approach angles of 5, 12.5, and 20 degrees, were conducted on each curb type. Such vehicle responses as redirection, trajectory, path, roll and pitch, and acceleration were observed and evaluated. The model results were found to correlate well with the full-scale results, and its applicability as a tool for evaluating vehicle response to a wide range of curb configurations appears to have been validated. The findings of the study suggest that curbs of the configurations tested have no redirection capabilities to enhance safety in a high-speed travel environment, and some may even reduce safety, especially when a curb-guardrail combination exists, by causing vehicle ramping. A review of the AASHTO policy on curbs presented in the published policy on geometric design for rural highways, to determine the desirability of revisions in the light of the findings of this project, seems appropriate. The evaluation process described may also be found to have application in optimizing the redirection capabilities of curbs that may be appropriate for use in low- to moderate-speed environments more typical of urban areas.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed as Task 5 under NCHRP Project 20-7 by the Texas Transportation Institute of Texas A&M University. This project is concerned entirely with research requested by the AASHTO Standing Committee on Engineering and Operations to assist it in fulfilling its responsibilities. Principal investigator for the project is Charles J. Keese, Director, Texas Transportation Institute; task supervisor was R. M. Olson, Research Engineer, Texas Transportation Institute.

Development of the full-scale test procedures and studies related to them was under the direction of G. D. Weaver, Assistant Research Engineer. Modification of the HVOSM, analysis of the test data, and correlation with the simulation model were conducted by E. R. Post, Assistant Research Engineer, and H. E. Ross, Jr., Associate Research Engineer. This report represents a cooperative effort with individual sections authored by the researcher responsible for that particular aspect of the study.

EFFECT OF CURB GEOMETRY AND LOCATION ON VEHICLE BEHAVIOR

SUMMARY

Curbs commonly are provided along streets, in channelized intersections, along medians, along ramps, and the like. When a vehicle scrubs or impacts a curb, curb shape and dimensions decidedly affect vehicle trajectory and the likely potential for driver recovery of vehicle control. Knowledge of vehicle action on impact can be a major tool in design decisions as to the use of (or omission of) curbs and their specific location in relation to the edge of a traveled lane. A related issue is the lift effect of a curb located along a guardrail or a bridge rail, either close to or at the face of the rail.

The approach taken to investigate the effects of curbs on vehicle behavior included a combination of full-scale testing and simulated impacts using the Highway Vehicle-Object Simulation Model (HVOSM). Three curbs (AASHTO Types C, E, and H) were selected for detailed study because they represent the curb configurations most commonly used throughout the U.S. A fourth configuration, designated Type X, was selected as an experimental barrier curb. The dimensions of the 13-in.-high Type X curb are those of the lower portion of the New Jersey concrete median barrier.

Eighteen full-scale tests were conducted on Types C and E curbs. A series of nine tests was conducted on each curb at 30, 45, and 60 mph and 5-, 12.5-, and 20-deg encroachment angles. These tests were simulated using HVOSM and the results were compared with those of the full-scale tests.

Twelve curb impacts were simulated on each of curb Types C, E, H, and X. The simulations included impacts of 30, 45, and 60 mph at 5, 12.5, and 20 deg and a 75-mph impact at 5, 10, and 15 deg.

The full-scale tests and parameter study simulations were evaluated to determine the effect of a curb on such vehicle responses as redirection, trajectory, path, roll and pitch, and accelerations.

The major findings are:

1. Curbs 6 in. high or less and of configurations similar to that of AASHTO curb Types C, E, or H will not redirect a vehicle at speeds above 45 mph and encroachment angles greater than approximately 5 deg. It is apparent that the speeds at which redirection is achieved are considerably less than those expected on modern rural highways. Therefore, curb Types C, E, and H are not satisfactory for installation where redirection is the primary design intent.

2. Curbs similar to Types C, E, and H can produce, under certain speed and angle impact conditions, vehicle ramping to a height at which the vehicle will vault a 27-in. guardrail located behind the curb. The guardrail offset distance necessary to restrain the vehicle (redirect the vehicle before its maximum rise is achieved) is dependent primarily on the exit angle, speed, and curb geometry. Guardrail height and placement behind a curb should be determined by analysis of expected impact conditions.

3. Curbs 6 in. high can cause a vehicle to impact a 27-in. guardrail (12-in.

W-beam at 2-ft offset) at a point below the lower edge of the rail face, thus creating the possibility of snagging. Consideration should be given to the use of a rub rail on guardrail located behind a 6-in. curb.

4. Impacting curbs 6 in. high or less can be reasonably expected to produce minor or no injury. An automobile will cross the curb at highway speed with ease and, unless a secondary impact occurs, the vehicle path can be expected to deviate only slightly from the initial encroachment path.

5. Curbs 13 in. high and of Type X configuration appear to have satisfactory redirection capabilities for impact conditions of 45 mph or less at angles of less than 12.5 deg. This type curb however, is not satisfactory for installation where 60-mph or greater operating speeds are expected because severe accelerations are produced when the vehicle crosses the curb.

6. HVOSM correlated well with full-scale tests results. Based on this correlation, HVOSM is considered to be validated for curb impacts and provides a useful tool with which to investigate a variety of curbs under the expected range of impact conditions.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

Historically, curbs have been grouped in two general classes —"barrier" and "mountable"—and throughout the years numerous designs have evolved for each. Curbs normally are not used on new rural highways, but can be found on many sections of older highways because that was accepted practice at the time of construction. However, curbs are often included in the design of highways through urban and semi-urban areas.

PROBLEM STATEMENT

In many cases it appears that use or omission of curbs is determined by a design engineer's personal opinion. Similarly, the selection of a particular curb cross-section seems to be made with little consistency. In one locale a 6-in. curb may be considered to act as a mountable curb and, hence, is installed where vehicle encroachment is intended and encouraged. In another area, the same curb may be considered to fall within the general class of barrier curb and is installed to deter encroachment or even with the thought that it will in fact redirect an errant vehicle under most impact conditions.

Curbs constitute a continuous roadside obstacle (as opposed to a point hazard such as a single-pole sign support) because they project above a traveled lane for appreciable lengths and are therefore highly subject to impact by a vehicle leaving the lane at any location within the curb length. A curb located in front of a guardrail or other fixed object may cause an impacting vehicle to ramp sufficiently to collide with the second obstacle in an airborne mode, or even to vault over it.

Decisions to use or omit curbs at certain locations must be tempered with objective facts concerning vehicle behavior and operating conditions upon impact. With the exception of only a few types of curbs, little or no criteria exist for determining proper curb type or location.

OBJECTIVES

The primary objectives of this study were to:

1. Select for study several of the more widely used typical curbs from the many types in use.

2. Study the effects of these curbs on a vehicle impacting them at speeds and angles consistent with highway operating conditions where such curbs are used.

3. Report the study findings in a manner amenable to preliminary development of criteria for the use (or omission) of curb types on rural highways under selected design intents.

RESEARCH APPROACH

Investigations of the effects of curb impact on vehicle behavior included a combination of simulated impacts using the Highway Vehicle-Object Simulation Model (HVOSM) and full-scale testing. The research approach included:

1. The selection of widely used, typical curb configurations to be investigated.

2. The conduct of full-scale vehicle impact tests on selected curbs to observe vehicle behavior and obtain field data for comparison with HVOSM-predicted response.
3. Thc simulation of full-scalc tcsts using IIVOSM.
4. Comparison of simulated vehicle behavior with test vehicle behavior for purposes of evaluating the HVOSM capabilities in predicting vehicle response to curb impact.
5. With satisfactory agreement, the simulation of impact of four selected curb types under a variety of speeds and encroachment angles.
6. Determination of the effect of the curbs on such aspects of vehicle response as roll and pitch angles, accelerations, trajectory, and path.

CHAPTER TWO

FINDINGS

The investigation of vehicle-curb impact included 48 simulated traversals using HVOSM as well as 18 full-scale vehicle tests on two selected curbs. This chapter presents the results of the study. The full-scale tests were conducted to obtain field data for correlation with HVOSM. Since close correlation was obtained, the more extensive parameter study was conducted with HVOSM and, hence, the findings are based primarily on the simulation study.

CURBS SIMULATED

A review of standard drawings from approximately 30 states led to the selection of three curb configurations—Types C, E, and H, AASHTO * "Blue Book" (*1*) designations—that are representative of current installations. Although some states use modified versions, these three curb types are widely used and therefore were selected for detailed study. They represent curbs used at locations where vehicle mounting is expected or intended and where encroachment is not desirable nor intended. Traversals of these three curb types, shown in Figure 1, were simulated at the speeds and angles given in Table 1. HVOSM simulations are discussed in detail in Appendix A.

Several considerations led to the exclusion of AASHTO Types A, B, or C curbs having vertical faces. In preparing the work plan, the researchers were informed that a contract was pending with another research agency to investigate vehicle response on impact with the AASHTO Type A curb of 6- and 9-in. heights and the Type G curb in a 6-in. configuration. The Type B curb was omitted from the study because available literature (*2*) indicated a prior record of unsafe experiences. The two AASHTO "barrier" curbs (Types A and B) thus were ruled out for consideration. Although the vertical-faced Type C curb is used by some states as a barrier curb, a review of several states' curb-design drawings indicated that the most widely used Type C curb was not vertical-faced, but had a slight batter. Therefore, the Type C curb having those batter and radii measurements as shown in Figure 1 was selected for the study.

Because no AASHTO barrier curb was included in the study, a fourth curb, designated Type X, was selected as an experimental barrier-curb configuration. The dimensions of Type X curb are those of the lower portion of the New Jersey concrete median barrier (CMB), as shown in Figure 2. Analysis of full-scale tests of the CMB indicated that a modified version of the barrier had potential as a barrier curb. Tests showed that, for moderate to low encroachment angles, vehicle redirection was produced by tire-curb interaction forces alone (with slight or no sheet-metal contact), and the tire climbed no higher than 13 in. on the face of the CMB (*3*).

FULL-SCALE TESTS ON CURBS

Eighteen full-scale tests were conducted to obtain field data for correlation with the HVOSM predictions. The tests consisted of a series of nine impacts each on AASHTO Types C and E curb configurations. Each series included 30-, 45-, and 60-mph impacts at 5-, 12.5, and 20-deg approach angles. The vehicle in each test was driven by a professional test driver. All tests were conducted in a "hands-off" steering mode. Geometry of the two full-scale-test curbs Types C and E and test installations are shown in Figures 1 and 3, respectively. Table 2 gives the test sequence and a summary of the full-scale test results. Appendix B is a detailed discussion of the test procedures. Appendix C translates the film analyses of the full-scale impact tests into a form suitable for comparison with and validation of HVOSM-predicted vehicle behavior characteristics.

EVALUATION CRITERIA

Evaluation of vehicle behavior during and immediately after impact with a curb centered on three factors—vehicle path, vehicle attitude, and vehicle accelerations. The degree to which the curb redirects the vehicle can be determined from the path. Vehicle attitude, defined in terms

* American Association of State Highway and Transportation Officials; formerly AASHO.

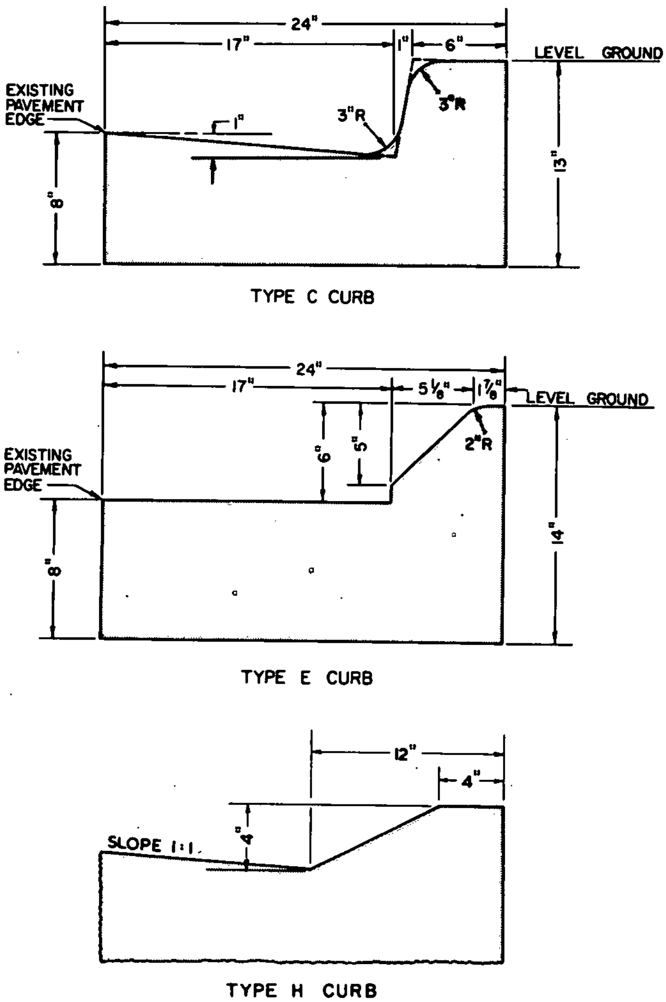

Figure 1. Geometry of AASHTO Types C, E, and H test curbs.

of the front bumper height and the roll and pitch angles, provides a description of vehicle behavior in general, and in particular when contact with a guardrail occurs after curb traversal. Vehicle accelerations provide indicators of the severity of the curb impact.

Figures 4 and 5 show the typical data obtained in the simulated tests. (Similar figures are presented in Appendix E for all 48 tests.) When redirection occurred, the figure showing bumper trajectory was omitted.

Vehicle accelerations were used in conjunction with a severity-index relationship to determine the relative severity of impact with the curbs. The severity index (*4*) is an interaction formula based on actual and tolerable accelerations in the longitudinal, lateral, and vertical directions.

COMPARISON OF SIMULATION WITH FULL-SCALE TESTS

The full-scale tests and their simulated counterparts were compared on the basis of vehicle path after impact, change in speed as a result of curb impact, and vehicle attitude (roll, pitch, and vertical rise with respect to the curb). Generally, as shown in Appendix D, the HVOSM predic-

TABLE 1

CURB COLLISIONS SIMULATED [a] BY HVOSM (48 SIMULATED TESTS)

	ENCROACHMENT ANGLES (DEG) AT SPEEDS (MPH) OF			
CURB	30	45	60	75
Type C	5	5	5	5
	—	—	—	10
	12.5	12.5	12.5	—
	—	—	—	15
	20	20	20	—
Type E	5	5	5	5
	—	—	—	10
	12.5	12.5	12.5	—
	—	—	—	15
	20	20	20	—
Type H	5	5	5	5
	—	—	—	10
	12.5	12.5	12.5	—
	—	—	—	15
	20	20	20	—
Type X	5	5	5	5
	—	—	—	10
	12.5	12.5	12.5	—
	—	—	—	15
	20	20	20	—

[a] All simulation conducted in a hands-off steering mode.

tions agreed closely with the test results; hence, the model was considered sufficiently validated to use in the parametric investigation of four curbs, which data are given in Appendix E. Comparison between the HVOSM predictions and the test results is presented in the following discussion.

Vehicle Path

During curb traversal, and immediately thereafter, HVOSM and the test results compared favorably with regard to vehicle path, with the exception of three tests (N-11, N-12, and N-17). In these tests HVOSM predicted redirection, whereas the full-scale-test vehicle crossed the curb.

Examination of the results shows that, at a lateral distance of between 5 and 10 ft behind the curb, the test vehicle usually deviated slightly to the right of HVOSM predictions. The deviation of paths may be attributed to the value of steering torque used in the HVOSM.

Vehicle Speed

Although the differences were not considered to be significant, the test vehicle speed decreased at a faster rate than that of HVOSM. Aerodynamic forces and inertial drag of the engine, drive shaft, and so forth influence the rate of deceleration in a free-rolling (no acceleration control) mode. HVOSM does not account for these factors.

Vehicle Attitude

For the purposes of this study, vehicle attitude is defined in terms of the bumper height (right front portion) and the pitch and roll angles of the vehicle. These three quantities are plotted as a function of the lateral position of the right front bumper. Also, for tests No. N-7 and N-18, selected frames of high-speed film are compared with perspective drawings of HVOSM output (see Fig. D-19 and D-20). With three exceptions (tests No. N-11, N-12, and N-17), the attitude comparisons agreed well between test data and HVOSM predictions.

Disparities in the comparisons are partly attributable to errors inherent in reducing film data and partly to idealizations used in the simulation. Disparity between test results and HVOSM predictions was more apparent in the high-speed tests, particularly between the predicted roll and bumper rise and that measured from the test data. Also, the driver expressed the opinion that the 60-mph tests resulted in less front-end rise and roll than occurred in some of the lower-speed tests. A discussion of difficulties encountered in comparing test data and simulation predictions is contained in Appendix B. Notwithstanding these difficulties, comparisons were generally satisfactory. Confidence in the simulation technique led to the use of HVOSM to perform a parametric study of the four curbs listed in Table 1. A discussion of this study follows.

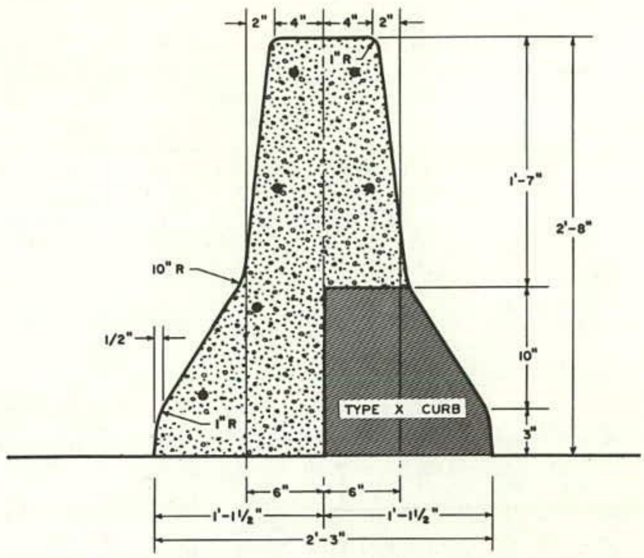

Figure 2. Geometry of the Type X curb and its relationship to that of the New Jersey concrete median barrier.

HVOSM STUDY OF SELECTED CURBS

The primary considerations established for evaluating safety benefits of curbs following impact by a vehicle were:

1. Redirection capability of the curb.
2. Vehicle trajectory and path imparted by curb impact.
3. Degree of vehicle pitch and roll imparted by curb impact.
4. Vehicle accelerations.

The simulated curb collisions will now be examined collectively in each of these categories. Table 3 presents a summary of the findings. Appendix E contains roll, pitch, and trajectory data for each simulated curb impact.

Curb Redirection Capabilities

With the exception of the 13-in. Type X curb, the vehicle crossed the curbs at all speeds and angles in excess of 30 mph and 5 deg with very little path redirection toward the curb. Even at 30 mph and 5 deg, the vehicle's right wheels crossed the 4-in. Type H curb, with redirection being caused by the left wheels against the curb face. In contrast to the apparent ease of vehicle mounting and lack of redirection capabilities of these curbs, the Type X curb redirected the vehicle in all impacts except the high-angle and -speed combinations (45 mph, 20 deg; 60 mph, 20 deg; and 75 mph, 15 deg). At these conditions, the vehicle crossed the 13-in. curb with significant peak and average accelerations as to imply passenger injury. HVOSM predicted vehicle rollover under the 75-mph, 15-deg condition.

Although curb Type H is designed primarily as a mountable (traversable) curb and, as such, its redirection capabilities would be expected to be low, it was evaluated under this criterion along with the other curbs to confirm this effect. Table 3 indicates that this curb redirected the test

Type C Curb in Foreground

Type E Curb in Background

Figure 3. Test curbs showing vehicle encroachment paths.

TABLE 2

SUMMARY OF FULL-SCALE TEST[a] RESULTS FOR CURB TYPES C AND E

TEST NO.	SCHEDULED APPROACH SPEED (MPH)	ACTUAL APPROACH SPEED (MPH)	SCHEDULED APPROACH ANGLE[b] (DEG)	ACTUAL APPROACH ANGLE (DEG)	MAX. RISE ABOVE CURB[c] (IN.)	MAX. PEAK VERTICAL ACCELERATION G FORCES	REMARKS
Curb Type E:							
N-1	30		5	—	—	—	Camera inoperative.
N-2 (rerun)	30	30.4	5	5.1	24.1	—	Car redirected by curb.
N-3	45	45.6	5	5.0	24.3	—	Slight redirection but all wheels crossed curb.
N-4	60	59.3	5	4.6	23.9	2.0	No vehicle redirection.
N-5	30	32.0	12.5	11.6	20.8	1.0	No vehicle redirection.
N-6	45	45.3	12.5	11.1	23.7	2.0	Slight undercarriage contact.
N-7	60	63.6	12.5	12.6	23.5	4.0	Appreciable undercarriage contact.
N-8	30	32.7	20	18.5	23.5	1.8	No vehicle redirection.
N-9	45	41.8	20	18.7	21.9	3.0	No vehicle redirection.
N-10	60	63.0	20	17.6	23.3	3.6	No vehicle redirection.
Curb Type C:							
N-11	30	34.2	5	4.9	26.2	1.0	Redirected smoothly (right wheels crossed curb).
N-12	45	44.7	5	5.1	24.8	1.0	Slight redirection toward curb but all wheels crossed curb.
N-13	30	34.2	12.5	11.2	23.8	1.8	Rim contact with curb —no damage to rim or tire.
N-14	45	43.5	12.5	12.8	23.1	2.6	No vehicle redirection.
N-15	30	32.1	20	17.4	22.1	2.4	Suspension bottomed "hard" — front wheels knocked out of alignment.
N-16	45	43.0	20	18.4	23.5	4.6	Right front wheel knocked out of alignment.
N-17	60	66.5	5	5.1	24.3	1.2	Severe suspension bottoming shock but no alignment damage.
N-18	60	62.2	12.5	12.3	21.4	4.2	Same as N-17.
N-19	60	61.5	20	18.6	23.0	4.0	Same as N-17. Ball joint became loose.

[a] All tests were conducted in a hands-off steering mode.
[b] Angles obtained from film analysis over time period of approximately 150 milliseconds.
[c] Bumper rise obtained from film analysis.
[d] Peak vertical accelerations obtained from accelerometer visicorder traces.

vehicle only at very low speeds and angles and produced very little front-end rise during traversal.

The practically nonexistent capability of curbs 6 in. or less to redirect a vehicle operating at highway speed would indicate that curbs of this height placed with the intent of redirection are creating an additional hazard rather than alleviating potential vehicle impact with an obstacle behind the curb. Further, as discussed subsequently, the hazard is compounded because the curb causes a crossing vehicle to ramp.

Based solely on the simulated impacts on the Type X curb, it appears that a 13-in. curb of this configuration represents a height which will, under impact conditions of low angle and/or low speed (30 mph impacts, and those of low angles at higher speeds), redirect a vehicle. However, the probability of a vehicle leaving the travel lane at a 20-deg angle and speed above 45 mph is not so small that it can be considered insignificant. It would be expected that these higher encroachment angles and speeds would occur on a horizontal curve (i.e., on-ramp or off-ramp) rather than on a tangent section. On tangent sections where probable exit angles would be lower at the 60- to 70-mph operating range, the Type X curb may have potential as a barrier curb in locations where guardrail normally is used

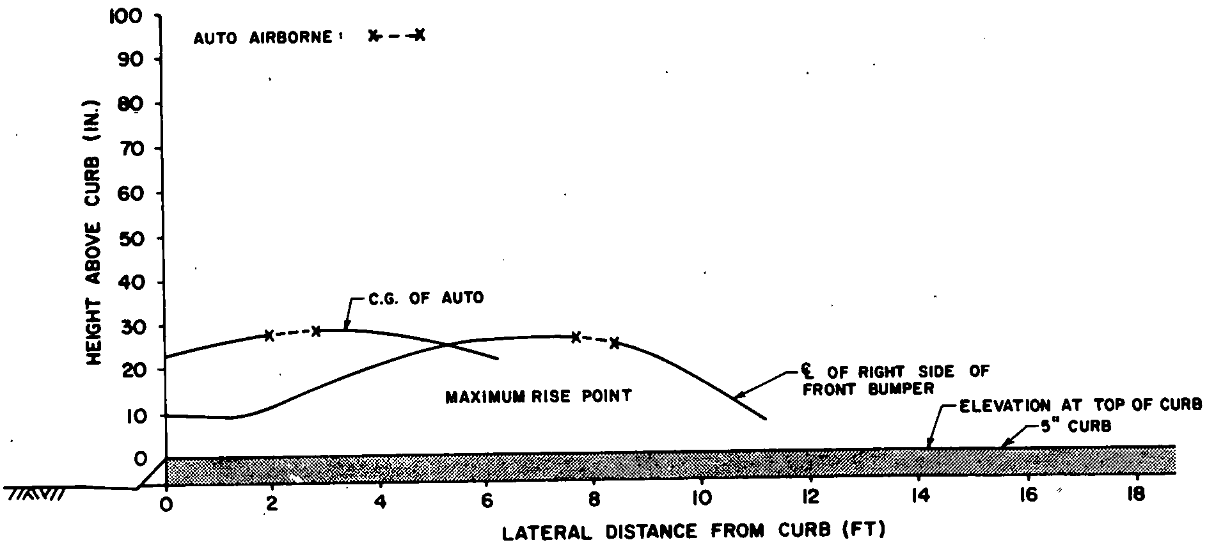

Figure 4. Vertical rise of vehicle in Type C curb simulated impact: 60 mph at 12.5-deg angle.

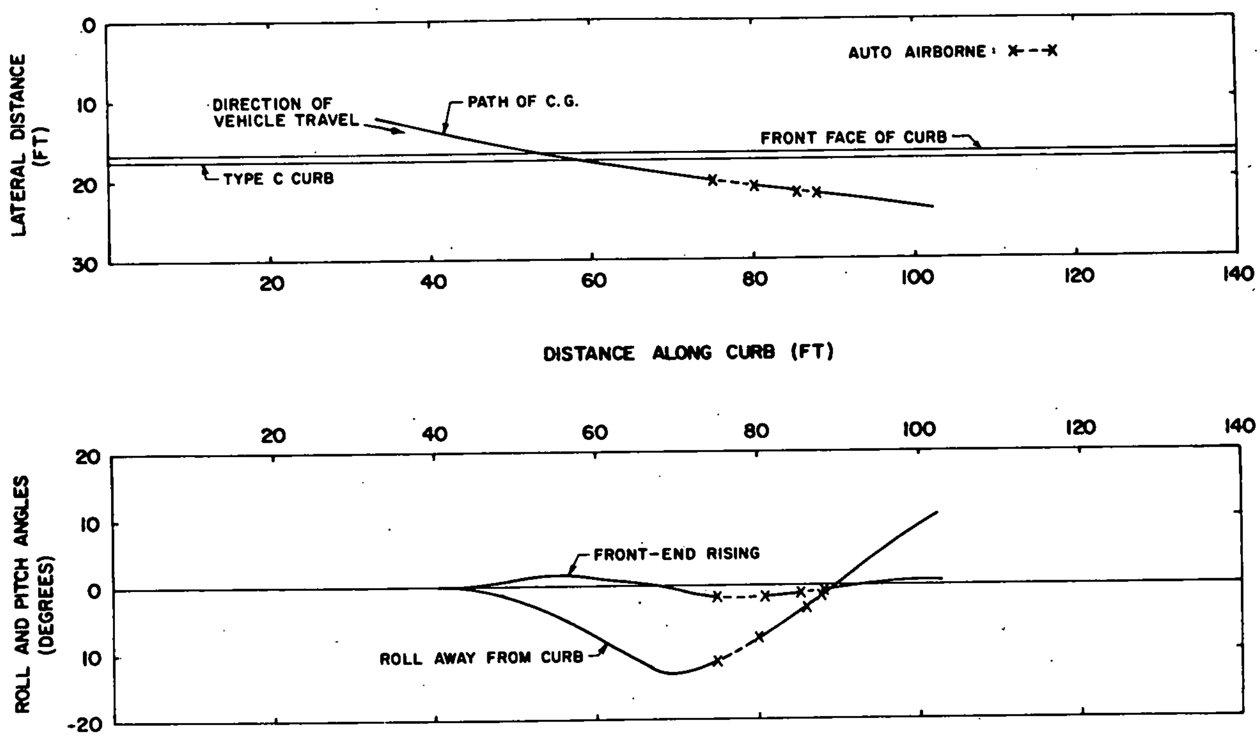

Figure 5. Path, roll, and pitch of vehicle in Type C curb simulated impact: 60 mph at 12.5-deg angle.

to deflect a vehicle. The Type X curb does not appear to be suited for placement along curving roadways such as ramps or high-speed direct connections, because higher encroachment angles may be achieved at these locations and the vehicle ramping characteristics of this curb make it definitely undesirable at locations where vehicle crossing can occur.

Vehicle Trajectory

Knowledge of the lift effect of a curb on a vehicle after impact is of primary concern in developing criteria for selection or omission of curbs in front of guardrails, bridge rails, or in medians. Investigation of vehicle trajectory received major emphasis.

Vehicle attitude after impact influences the severity of a secondary impact, particularly with a guardrail or breakaway support. If the front end of the vehicle is rising (positive pitch angle), rolling to the left (negative roll), and is ramped as it crosses the curb, it is quite possible that the front bumper will act as a "skid plate" when impacting a guardrail behind the curb, resulting in a secondary launching effect. This occurrence is especially probable if the front bumper is sloped back at the bottom. When the vehicle ramping is sufficiently high enough to allow the bumper to equal or exceed the guardrail height, there is

TABLE 3

SUMMARY OF SIMULATED VEHICLE RESPONSE TO CURB IMPACT

CURB	VEHICLE SPEED (MPH)	IMPACT ANGLE (DEG)	MAXIMUM ROLL ANGLE (DEG)	MAXIMUM PITCH ANGLE (DEG)	MAXIMUM BUMPER HEIGHT ABOVE CURB (IN.)	LATERAL DISTANCE TO MAX. RISE POINT (FT)	BUMPER HEIGHT ABOVE CURB AT 2-FT OFFSET (IN.)
Type C (6-in.)	30	5	−11.5	1.5	—[a]	—[a]	—[a]
	30	12.5	−10.0	2.9	—[a]	—[a]	—[a]
	30	20	+8.8	2.9	22	5	12
	45	5	12.6	1.0	—[a]	—[a]	—[a]
	45	12.5	−9.5	−3.6	—[a]	—[a]	—[a]
	45	20.0	−8.9	3.0	26	8	11
	60	5	15	+1.5	—[a]	—[a]	—[a]
	60	12.5	−13	2.0	27	7	13
	60	20	−8	2.0	29	10	10
	75	5	+14.5	3.5	—[a]	—[a]	—[a]
	75	10	−15.5	2.0	30	6	13
	75	15	−10.2	1.8	30	10	12
Type E (6-in.)	30	5	−10.2	2	—[a]	—[a]	—[a]
	30	12.5	−9.5	2	21	4	13
	30	20	−8	2.5	21	6	11
	45	5	−11	2	—[a]	—[a]	—[a]
	45	12.5	−11	2	23	5	12
	45	20	−8	2.2	25	8	11
	60	5	−11.2	2	23	3	17
	60	12.5	−12	2	25	6	13
	60	20	−9.5	2.5	31	10	11
	75	5	−12	1.5	23	4	16
	75	10	−13	2	25	6	13
	75	15	−11	2	31	9	12
Type H (4-in.)	30	5	−6	1	—[a]	—[a]	—[a]
	30	12.5	−5	1	18	5	13
	30	20	−30	1	18	9	12
	45	5	−7	1	20	3	15
	45	12.5	−5	1	—[a]	—[a]	—[a]
	45	20	−4	1	20	10	14
	60	5	−7	1	20	4	15
	60	12.5	−5	1	20	8	13
	60	20	−3	1	20	10	13
	75	5	−7	1	20	5	13
	75	10	−6	1	20	10	13
	75	15	−4	1	20	8	13
Type X (13-in.)	30	5	−4	1	—[a]	—[a]	—[a]
	30	12.5	−8	7	—[a]	—[a]	—[a]
	30	20	−16	10	—[a]	—[a]	—[a]
	45	5	+3	3	—[a]	—[a]	—[a]
	45	12.5	−28	9	—[a]	—[a]	—[a]
	45	20	−25	9	53	5	18
	60	5	−2	3	—[a]	—[a]	—[a]
	60	5	−2	3	—[a]	—[a]	—[a]
	60	12.5	−48	9	—[a]	—[a]	—[a]
	60	20	−30	8	63	8	11
	75	5	−8	3	—[a]	—[a]	—[a]
	75	10	−51	9	—[a]	—[a]	—[a]
	75	15	−180	7	85	9	15

[a] Curb was not crossed, vehicle was redirected.

little doubt that the car would cross, or at least snag and be flipped or rolled, over the guardrail. It is difficult to estimate the vertical contact point on a guardrail below which a vehicle would be restrained and redirected. This point would differ for various guardrail configurations and lateral stiffness properties and would be influenced by many vehicle characteristics, such as impact conditions, bumper shape, and attitude after curb impact.

It has been suggested that vehicle trajectory caused by curb impact differs widely for various automobiles—that a heavy automobile with "heavy-duty" suspension would react considerably different upon impact than would a similar one with a "soft" suspension system. The difference in trajectories was found to be small when the simulation study test data obtained from a car having heavy-duty suspension were compared to those for the standard-suspension vehicle.

Although guardrails and bridge rails first come to mind when considering secondary impacts behind a curb, breakaway signs or luminaire supports as objects of secondary impact deserve consideration. Breakaway supports perform best when impacted near their bases. Should a colliding vehicle be airborne and impact a support well above its base, the structure may not function as intended. Investigation of breakaway support efficiency is beyond the scope of this study, but it is suggested that collision damage would be aggravated should a vehicle collide with a breakaway structure that happened to be located laterally at the point where the vehicle's rise was maximum.

Because bumper shapes differ widely, the mid-point of the right front corner (16.75 in. from ground level) was selected as the reference point to determine vertical rise with respect to lateral distance behind each curb. Vehicle trajectories resulting from impacts with each of the four curbs are shown in Appendix E.

The maximum trajectory rise and its point of occurrence with respect to the curb face are influenced by vehicle speed and angle at which the curb is impacted. Figures 6 and 7 show typical effects on the trajectory by varying either speed or impact angle. For 6-in. curbs, an increase in either speed or impact angle resulted in a shift of the maximum rise point behind the curb and upwards. An increase in angle produced a greater shift in both lateral and vertical position of the maximum rise point for a speed differential at the higher speeds (60 to 75 mph) than for a low-speed differential. For low-angle impacts, an increase in speed resulted in a lateral shift, but not an appreciable increase in rise height. This behavior was confirmed for the 4-in. Type H curb. For this curb, throughout the angle spectrum, increased speed produced a lateral shift of maximum rise point from a distance of about 4 ft at 5 deg (average of 45 to 75 mph) to about 10 ft behind the curb face with very little increase (less than 2 in.) in maximum rise height. In fact, the maximum rise height did not increase a measurable amount for speed increases above 30 mph.

The maximum bumper rise was found to be dependent

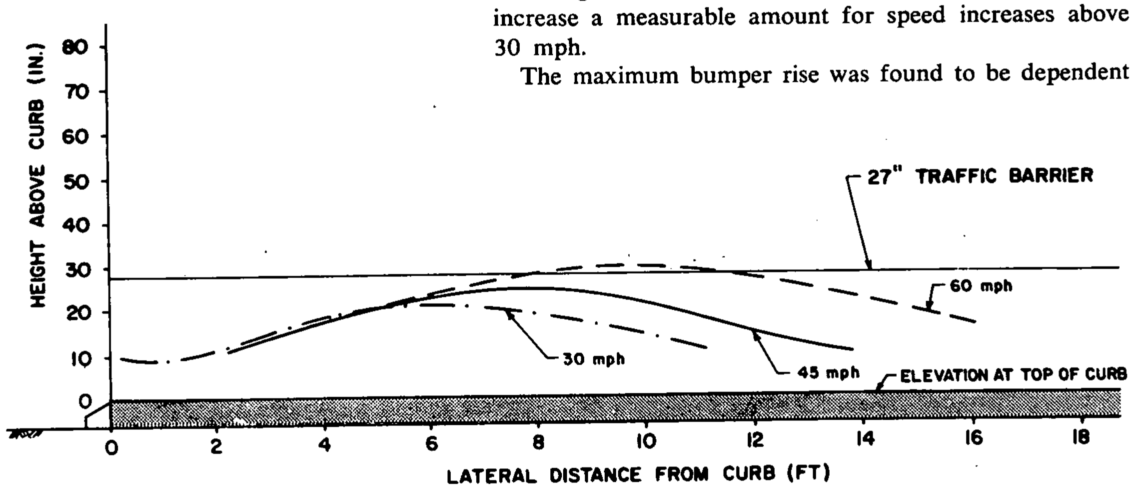

Figure 6. Effect of vehicle speed on vehicle trajectory in Type E curb simulated impact at 20-deg angle.

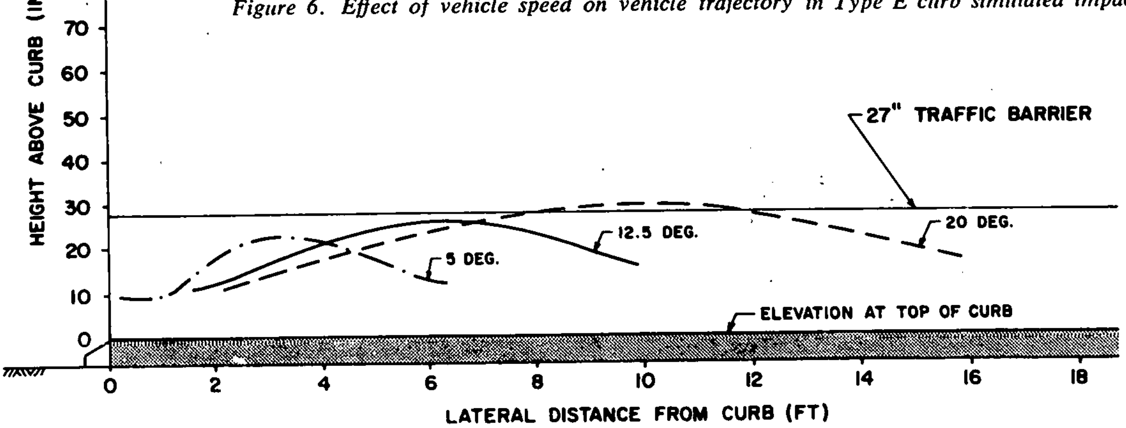

Figure 7. Effect of impact angle on vehicle trajectory in Type E curb simulated impact at 60 mph.

Figure 8. Accident involving curb and guardrail.

on the combination of vehicle roll and pitch caused by striking the curb. The roll is influenced by magnitude and rate of application of force through the right front wheel as it impacts the curb, and the degree to which roll is damped is influenced by the geometry of the curb and effect on the other wheels. For example, when a steep-faced 6-in. curb is struck, the right front wheel lifts quickly, which in turn distributes the load to the other three wheels, particularly to the left front wheel. If the vertical tire force is sufficient to "bottom" the suspension system, additional shock loads are introduced. The contribution of curb geometry to damping of the roll angle during left-wheel impact obviously differs with the height and the steepness of the curb face.

As one would expect, the pitch and roll angles produced by simulated collisions with Type C and Type E curbs were greater than those produced by the Type H curb. In many instances, the pitch and roll for the steeper-faced curbs were twice that for the Type H curb. It is noted, however, that the Type H curb geometry (of relatively low profile and small face slope) apparently combined the proper variables to produce a maximum rise height that is relatively independent of speed and angle. The maximum rise point offset (lateral position of maximum rise) is affected primarily by speed. Although the location of the maximum bumper rise point is important if it occurs where a guardrail or other obstacle would normally be located, the trajectory within the first few feet behind the curb is usually of more significance. In other words, an unimpeded trajectory resulting in a 36-in. maximum rise at a lateral distance of 10 ft behind the curb is of little significance when a 27-in. guardrail happens to be located 2 ft behind the curb and the vehicle's vertical rise at this point is only 15 in. Therefore, trajectory must be evaluated in terms of the potential for a secondary collision with an obstacle located behind the curb. For example, a curb separating a 10-ft shoulder from the outer travel lane, such as shown in Figure 8, would place a guardrail—normally located at a 2-ft offset from the shoulder—12 ft behind the curb. Because the maximum height of bumper rise occurred in the 8- to 10-ft range for high-speed, high-angle impacts on all curbs except Type X, a curb—particularly a 6-in. curb—located as described could easily contribute to a crossing vehicle's probability of having a severe secondary collision with the guardrail. Maximum rise for the Type C curb was greater than the standard 27-in. guardrail height for the high-angle 60- and 75-mph impacts and slightly less for the lower-speed, high-angle impacts.

The complete trajectory for each curb impact, shown in Appendix E, provides a method to investigate expected points of secondary vehicle collision with objects of various heights located at selected distances behind a particular curb. The maximum rise and the rise at the normal 2-ft offset are given in Table 3.

The bumper heights at the 2-ft offset were all equal to or less than the normal 21-in. contact height for a 27-in. W-beam guardrail. In fact, in some cases, and particularly those of high-speed, high-angle impacts on curbs Types C and E, the bumper contacted the rail at a point lower than normal. In several instances the bumper dipped downward slightly as the wheel impacted the 6-in. curb and then began to rise as the vehicle crossed the curb. The front overhang and angle at which the car approached the curb placed the right front bumper close to the guardrail before the right front wheel contacted the curb. Also, the lower edge of the guardrail (approximately 15 in. above level ground in normal configuration) is actually 21 in. above the pavement surface (15 in. plus the curb height). This, in conjunction with the initial dipping motion, would result in the bumper contacting the guardrail below the rail face creating the possibility of snagging.

An initial dipping motion of the bumper was not so evident for the 4-in. Type H curb. Contact with the guardrail, offset 2 ft behind the curb, occurred on the rail face for all

TABLE 4

ACCELERATION DATA FOR HVOSM VEHICLE ON IMPACT WITH CURB TYPE E

		PEAK ACCELERATIONS [a] AVERAGED OVER 2 MILLESECONDS			SEVERITY INDEX BASED ON SIMULTANEOUS ACCELERATIONS AVERAGED OVER 10 MILLISECONDS				MAXIMUM TIRE DEFORMATION [c] DURING CURB CONTACT (IN.)			
VEHICLE SPEED (MPH)	IMPACT ANGLE (DEG)	LONG. (G FORCES)	LAT.	VERT.	LONG. (G FORCES)	LAT.	VERT.	SEVERITY INDEX[b]	RF	RR	LF	LR
30	5	0.1	0.5	0.5	0.1	0.5	0.1	0.1	2.1	1.4	—[d]	—[d]
30	12.5	0.2	1.0	1.5	0.1	0.9	0.1	0.2	2.5	3.1	3.0	1.8
30	20	0.6	2.0	3.3	0.5	1.5	0.2	0.3	3.4	3.6	3.0	2.8
45	5	0.1	0.6	0.9	0.1	0.6	0.1	0.1	2.7	2.7	—[d]	—[d]
45	12.5	0.5	2.2	3.8	0.3	2.0	0.2	0.4	3.5	3.6	2.9	2.7
45	20	1.0	2.9	5.9	0.1	0.6	3.6	0.6	3.8	4.0	3.2	3.6
60	5	0.1	0.8	1.8	0.0	0.1	1.3	0.3	3.0	3.0	2.5	1.9
60	12.5	0.7	3.3	6.3	0.1	0.3	3.5	0.6	3.9	4.1	3.7	2.8
60	20	1.3	4.1	9.2	0.1	0.3	5.0	0.8	4.3	4.6	4.1	3.6
75	5	0.1	1.2	2.3	0.0	0.2	1.63	0.3	3.2	3.1	3.2	2.2
75	10	0.6	3.4	6.5	0.1	0.3	3.8	0.6	3.9	4.1	3.5	2.9
75	15	1.2	4.4	10.2	0.1	0.4	5.4	0.4	4.4	4.5	4.1	3.5

[a] The peak acceleration components may not occur simultaneously.
[b] See Appendix B for discussion of severity index.
[c] Individual tire contact occurs in order shown.
[d] Curb not mounted by tire.

TABLE 5

ACCELERATION DATA FOR HVOSM VEHICLE ON IMPACT WITH CURB TYPE X

		PEAK ACCELERATIONS [a] AVERAGED OVER 2 MILLESECONDS			SEVERITY INDEX BASED ON SIMULTANEOUS ACCELERATIONS AVERAGED OVER 10 MILLISECONDS				MAXIMUM TIRE DEFORMATION [c] DURING CURB CONTACT (IN.)			
VEHICLE SPEED (MPH)	IMPACT ANGLE (DEG)	LONG. (G FORCES)	LAT.	VERT.	LONG. (G FORCES)	LAT.	VERT.	SEVERITY INDEX[b]	RF	RR	LF	LR
30[d]	5	0.3	1.6	1.3	0.3	1.2	0.2	0.3	—[e]	—[e]	—[e]	—[e]
30[d]	12.5	1.1	5.1	5.1	1.0	4.5	1.4	0.9	—[e]	—[e]	—[e]	—[e]
30[d]	20	2.6	7.9	8.0	2.3	7.2	4.5	1.7	5.0	2.5	—[e]	—[e]
45[d]	5	0.5	2.9	2.8	0.4	2.2	0.2	0.6	—[e]	—[e]	—[e]	—[e]
45[d]	12.5	1.7	8.4	9.1	1.5	7.3	3.0	1.6	5.0	4.2	—[e]	—[e]
45	20	2.7	9.5	17.6	1.3	4.4	7.9	1.6	5.4	3.9	0.7	3.9
60[d]	5	0.3	5.2	1.5	0.2	4.2	0.1	0.8	—[e]	—[e]	—[e]	—[e]
60[d]	12.5	3.1	11.2	14.2	1.8	10.0	4.3	2.1	5.7	4.7	—[e]	—[e]
60	20	3.2	9.1	26.2	1.2	4.0	12.0	2.2	7.1	5.1	3.5	4.9
75[d]	5	0.4	5.1	5.4	0.1	4.8	0.2	1.0	—[e]	—[e]	—[e]	—[e]
75[d]	10	1.8	11.4	15.0	1.5	9.9	3.4	2.1	5.7	4.8	—[e]	—[e]
75[f]	15	2.4	9.3	25.1	1.0	4.6	11.6	2.2	6.8	5.8	3.8	4.2

[a] The peak acceleration components may not occur simultaneously.
[b] See Appendix B for discussion of severity index.
[c] Individual tire contact occurs in order shown.
[d] Auto redirected by curb.
[e] Curb not mounted by tire.
[f] Rollover.

angles and speeds. This is attributed to the gentle upward trajectory and little or no bumper dipping at wheel contact.

Type X curb's effect on vehicle trajectory is discussed last because it does not cause a colliding vehicle to perform in a manner similar to that experienced with the lower curbs. This study indicates that curb Type X is not suitable for locations where exit angles of 20 deg and operating speeds of 45 mph or greater can be achieved, because the test vehicle experienced appreciable roll angles (25 to 30 deg), high vertical accelerations, and climbed over the curb. The maximum bumper rise for 45- and 60-mph impacts at 20 deg was 53 and 63 in., respectively. The simulated car crossed the curb with a maximum rise of 85 in. after the 75-mph, 15-deg impact and rolled completely over to land approximately 19 ft behind the curb.

Vehicle Accelerations

Although it was the opinion of the researchers from the inception that vehicle accelerations would be small in all curb impacts with the exception of curb Type X, acceleration studies of simulated impacts on curbs Types E and X corroborated this belief. Tables 4 and 5 give acceleration data and severity indices (*4*) for these two simulated conditions.

Vehicle acceleration appears to be negligible because the time duration is short and peak accelerations are small. Thus, the speed change during a collision is slight. This was substantiated by accelerometer measurements in the full-scale tests (see Table 2). Severity indices were well below the level considered to cause serious occupant injury. For a given encroachment condition, the severity indices for curbs Types C and E were approximately equal and were small for all encroachment conditions examined, indicating that the types of injury that would occur would be minor or none at all.

The accelerations experienced in the Type X curb study cannot be considered insignificant. Assuming that a severity index of 1.0 represents a level at which unrestrained passengers experience serious injury, it can be seen from Table 5 that the Type X curb does not perform satisfactorily for speeds in the 60- to 75-mph range at angles greater than 5 deg nor for lower speeds at higher angles.

CHAPTER THREE

APPRAISAL AND APPLICATION OF RESULTS

APPRAISAL

Curbs are installed on highways in urban areas on and near bridges, at intersections for lane dividers, near underpasses, and in other selected locations. The diverse functions of curbs include (1) drainage, (2) delineation, (3) aesthetics, and (4) safety. Also, some curb configurations are intended to serve as barriers and others facilitate maintenance operations.

Examination of standard designs employed in more than 30 states indicated that these states follow the guidelines set out in the current Blue Book. A study of earlier guidelines (*5, 6*) suggests that the use of curbs dates to the time when highways were routed through cities. On such street routes, protective islands for pedestrians were necessary. Curbs also were used by passengers when stepping down from running boards of automobiles, and they served to redirect automobiles away from sidewalks. Photographs of early divided highways, on which speeds were limited, clearly show that curbs provide an attractive method of delineating the edges of the roadway. The evolution of curbs has been an orderly process of applying existing practices to new locations.

In urban areas, provision must be made for pedestrians on bridges and along the roadway. These pedestrian areas are usually separated from the roadway by a curb. Frequently highways are designed for a specific speed; and, although the speed limit may be increased at a later time, the geometrics of the highway and appurtenances such as curbs remain the same. Increased speeds, greater traffic volumes, and constantly changing vehicle capabilities can result in collisions, the severity of which can be aggravated by curbs. Beaton and Peterson (*7*) conducted full-scale crash tests in 1953 to ascertain the ". . . ability of various types of curbing to serve as a physical barrier to cars striking the curb, and also to determine the potential damage to both car and curb." Subsequently, Beaton and Field (*8*) reported findings of tests on bridge curbs and rails. These studies clearly demonstrated the behavior of an automobile following a collision with a curb. The "jump curves" presented in these earlier studies were examined and led to those presented in the present study.

Many states continue to use mountable curbs in medians and along the edges of roadways as well as guardrails in conjunction with curbs. A series of live-driver tests in Washington (*9*) clearly indicated that a mountable curb in the median did not produce redirection of a speeding automobile. Earlier, California conducted full-scale tests on raised medians in conjunction with development of cable median barriers. Standard-size automobiles and smaller sports cars easily mounted raised medians having 6-in. curbs (*10*).

In recent years, a slope-faced concrete median barrier has been adapted for use on bridges and as a barrier between the edge of the traveled way and fixed hazards such as bridge columns or steep-cut sections. Use of this configuration seems to be replacing the two-step barrier curb, AASHTO Type B curb (*1*). Full-scale tests (*11-13*) on "safety shape" median barriers and on an adaptation of their shape to bridge barriers (*14*) have led to the current trend for employing such barriers.

Often guardrails or bridge barriers are located behind curbs, and the behavior of colliding vehicles has been discussed by others (*2, 8, 10*). Such installations aggravate a secondary collision incident. However, the objective of the present study was to evaluate the effect of vehicle-curb impact on vehicle behavior. The results reported herein are aimed at operating conditions on high-speed facilities in rural and urban areas, but the lower-speed results may be applied to streets.

Redirection

None of the AASHTO curb designs investigated are satisfactory for installation on high-speed facilities where redirection is the primary design intent. Examination of Figures 9 and 10 leads to the conclusion that redirection may be expected when encroachment angles are 5 deg or less at speeds in excess of 60 mph. As one might anticipate, the Type X configuration is likewise unsatisfactory for high-speed facilities. Vehicle redirection is obtained at impact angles up to 10 deg at a speed of 60 mph; however, concomitant severe accelerations and roll angles are experienced.

Conventional curbs of the types studied in this project, as well as those investigations cited previously, do not function as barriers. The present study corroborates the findings of the California curb tests. At present, the most promising highway barrier concepts are the New Jersey safety shape, the General Motors Proving Ground bridge parapet design, and the California Type 20 bridge barrier. Although none of these designs fits the curb classification, it is clear from the present study and previous work that a curb height of 32 in. is required to achieve vehicle redirection.

Vehicle Attitude

Curbs similar to AASHTO Types C, E, and H can produce vehicle ramping under various combinations of speed and angle impact conditions such that there is a strong possibility that a vehicle will vault a 27-in. guardrail located behind a curb. The guardrail offset distance to restrain a ramped vehicle differs for various angles, speeds, and curb geometry. A secondary collision with guardrail located behind a curb can be compounded if the offset is such that the initial vehicle front-end dipping causes the bumper to snag beneath the rail face. Obviously it is uneconomical to remove all curb in front of guardrail; however, the use of rubbing rails is recommended to alleviate bumper snagging.

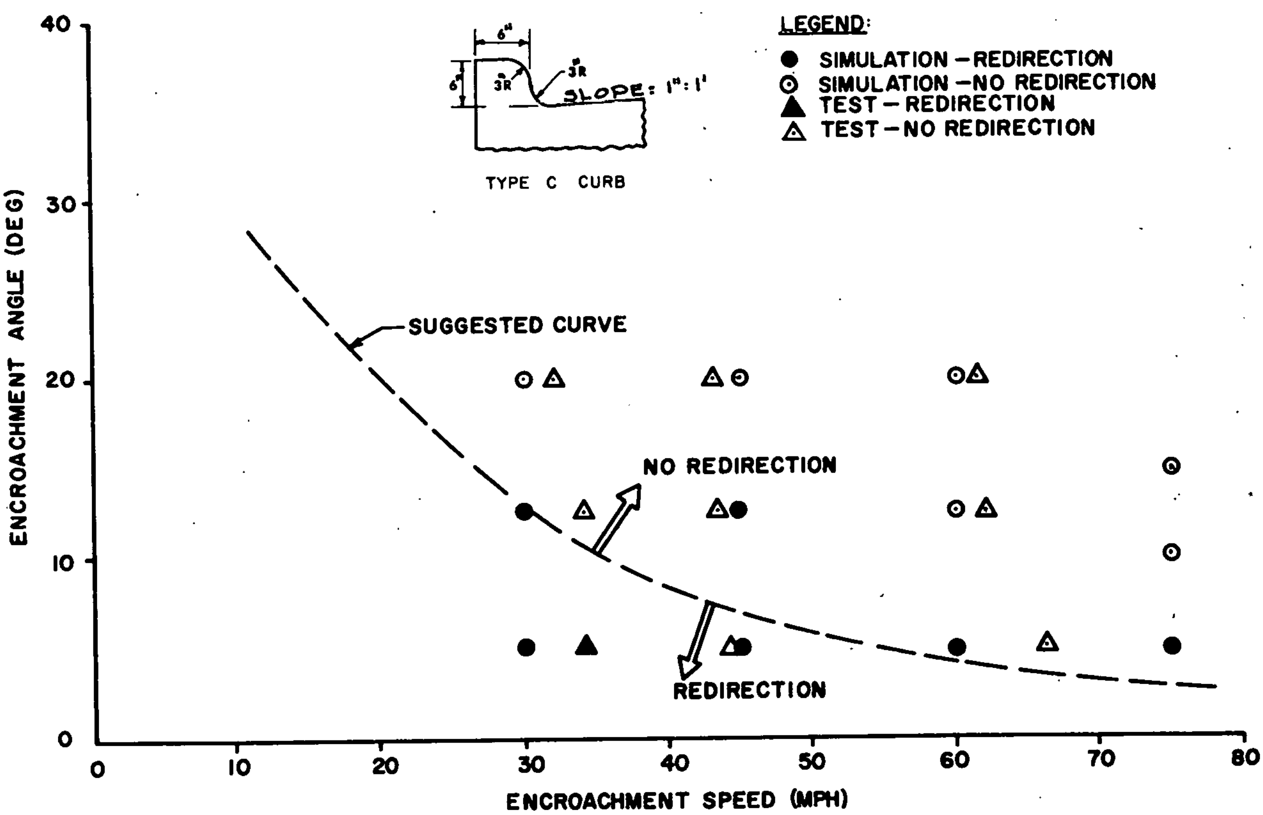

Figure 9. Vehicle redirection capabilities of Type C curb.

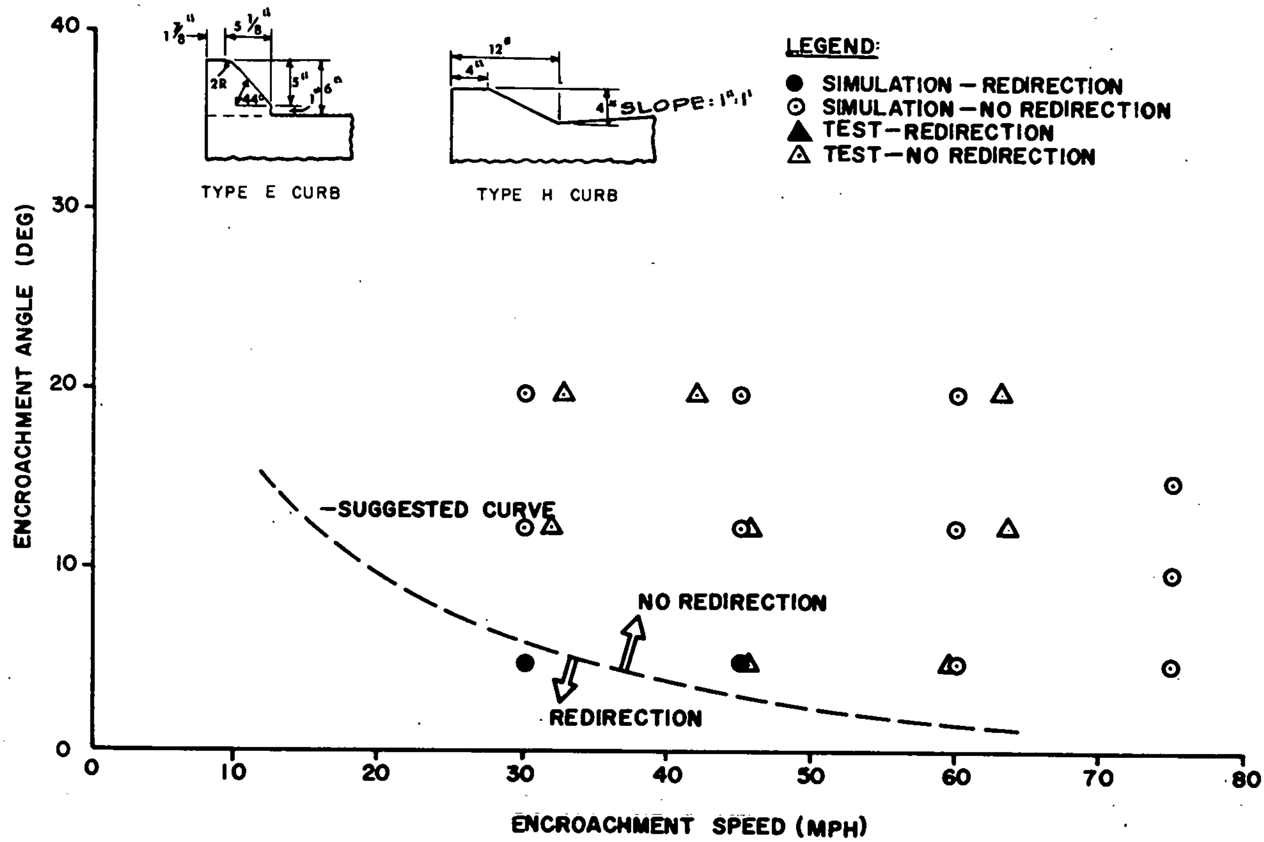

Figure 10. Vehicle redirection capabilities of Type E and H curbs.

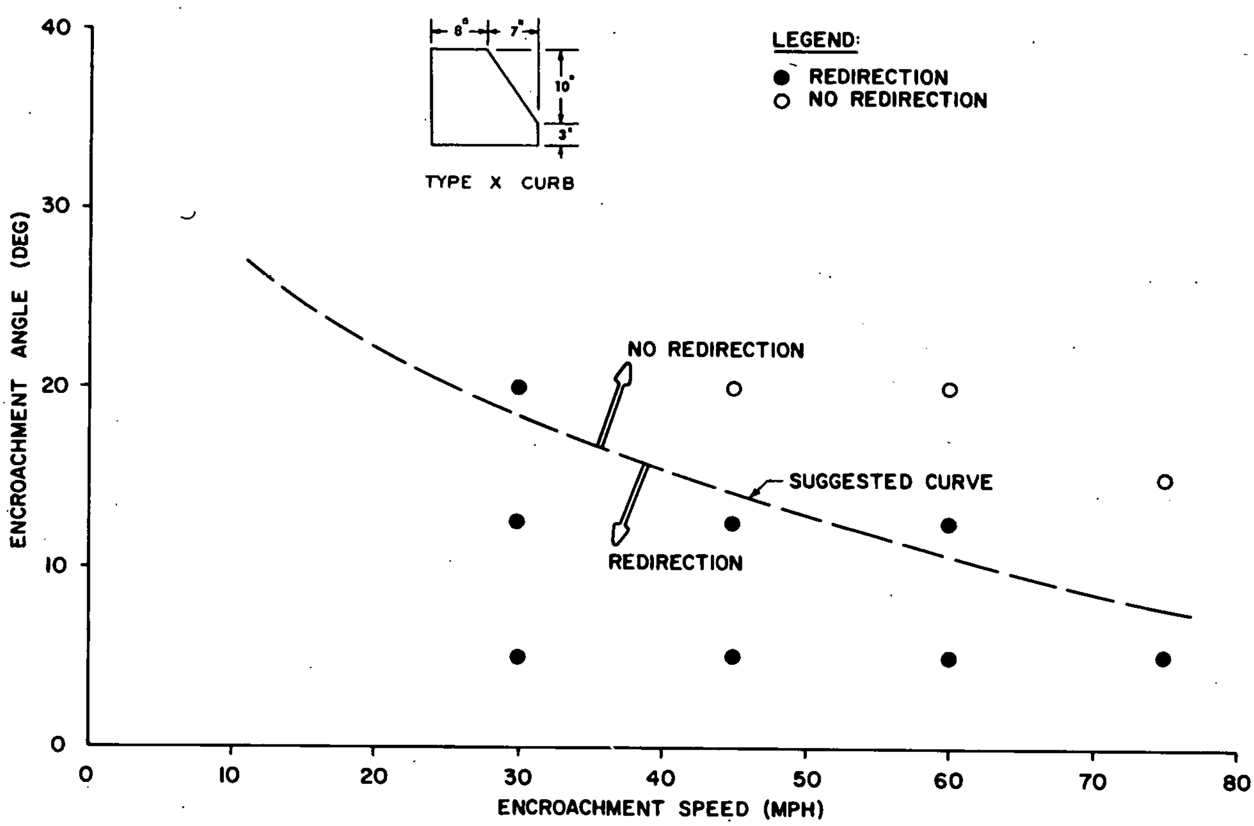

Figure 11. Vehicle redirection capabilities of Type X curb.

Maximum bumper rise occurs in the range of 8 to 10 ft behind 6-in. curbs. Therefore, existing curb-guardrail combinations in which the rail offset is in this range should be considered most critical.

Curbs of Type X configuration are unsatisfactory for high operating speeds because they can produce vehicle rollover.

Vehicle Accelerations

Curbs of 6 in. or less produce slight vehicle accelerations. However, although decelerations are slight, a curb aggrevates any collision resulting off the traveled lane because it represents a discontinuity in the vehicle path with which the driver must contend. Additionally, curb impact at high speeds is capable of damaging the vehicle steering mechanism (as was observed during the full-scale test phase of this study), which diminishes control of a car by its operator.

APPLICATION

The curbs investigated in this study offer no enhancement to safety on high-speed highways from the viewpoint of vehicle behavior following impact. For this reason, it is recommended that the use of curbs on high-speed highways be discontinued.

Figures 9 through 11 indicate that curbs *may* have potential redirection capabilities on low-speed facilities; however, the decision to construct them should be based on considerations other than redirection alone. Typical reasons for curb installation include delineation and drainage. Delineation and drainage can be achieved by other means that do not produce discontinuities in the roadway.

Curbs located in front of guardrails can aggravate a secondary collision with the guardrail by producing vehicle ramping. It is recommended that installation of curbs in front of guardrails be eliminated in future construction.

Finally, consideration should be given to removing existing curbs in front of guardrails on high-speed highways.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

It has been found that curbs offer no safety benefit on high-speed highways from the standpoint of vehicle behavior following impact. This conclusion is based on evaluation of vehicle impact under conditions considered reasonable for expected operating conditions. On the basis of this finding, it is concluded that omission of curbs along high-speed highways will enhance safety. Although curbs may improve delineation, it is suggested that other methods, such as painted edge lines or raised markers, should be employed. Curbs may be desirable for drainage, but this can be achieved in other ways on high-speed facilities.

When barriers are required to protect an errant vehicle, a full-height barrier should be considered, such as the configuration employed in the New Jersey concrete median barrier, which is becoming widely used.

The Blue Book, by its title and intent, presents policy guidelines applicable to rural highways. It is recommended that consideration be given in future editions to omitting all sections on curbs. Similarly, the "Red Book" establishes policy guidelines for an entirely different operating environment—urban areas; the findings of the study reported herein may be applicable in future editions.

SUGGESTED RESEARCH

In the researchers' opinion, further research regarding barrier curbs as such is not recommended. If a barrier is desired, a full-height barrier such as the concrete median barrier (rather than a conventional curb) should be used. In this respect, additional parametric studies are warranted to develop optimum geometric features for desired operational performance. Some present versions of HVOSM may be used to conduct necessary studies.

Although the results of this study lead to the conclusion that curb-guardrail combinations should not be constructed, it is realized that many such combinations do indeed exist on highways. If a vehicle's secondary impact with a guardrail is to be evaluated, full-scale tests are needed to determine vehicle behavior and the collision performance of the barrier under impact conditions. These effects can be determined by applying HVOSM once the present HVOSM capabilities have been expanded by developing barrier impact subroutines that can simulate vehicle impact for any impact altitude, or by a combination of HVOSM and full-scale tests.

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APPENDIX A

HVOSM MODIFICATIONS AND INPUT DATA

The capability of the Highway Vehicle-Object Simulation Model (HVOSM) developed by CAL (*15*) was extended in this study by increasing the number of curb faces that can be modeled. The existing HVOSM model initially was restricted to a curb with *two* faces, whereas the modified model now can idealize a curb with *six* faces.

A discussion of the modifications to the HVOSM follows the material presented on (a) the application of the modified curb subroutine, (b) the idealization of the four curbs investigated, and (c) the input data used for the test vehicle and the parameter study vehicle.

APPLICATION OF MODIFIED CURB SUBROUTINE

The modified curb subroutine can be used to idealize a curb configuration by a series of six or fewer straight-line segments as diagramed in Figure A-1. Each line segment is defined as a curb face.

The curb is located in a space-fixed coordinate axes system designated as X′, Y′, and Z′. The curb must be oriented in a direction parallel to the X′ axis. Lateral distances of the curb faces are defined by the Y′ coordinates (Y'_{ci}); vertical distances by the Z′ coordinates (Z'_{ci}); and rotational angles by the phi coordinates (ϕ_{ci}).

The sign convention of the *right-hand* coordinate axes system shown in Figure A-1 defines lateral distances of the curb faces as positive in a direction to the right; vertical distances as positive in a downward direction; and, rotational angles as positive in clockwise direction. Rotational angles are measured relative to the Y′ axis.

A restriction of the HVOSM program requires that the roadway or terrain adjacent to the curb be level (flat) and located at an elevation of zero; that is, $Z' = 0$.

Input data for a curb having six and fewer faces are contained on four IBM cards. The required format of the four cards is shown in Figure A-1. The first IBM card contains information on the number of curb faces, tire-curb friction coefficient, increment of integration, and the ICARD integer number of 15. The ICARD number is

HVOSM CURB IMPACT INPUT DATA

Card	Col. Nos.	Program Variable	Report Variable	Definition	Units
1	1-8	NCRBSL	-------	No. curb faces	-----
	9-16	AMUC	μ	Tire-curb friction	-----
	17-24	DELTC	Δt_c	Increment of integration	-----
	79-80	ICARD	-------	ICARD = 15	-----
2	1-10	YC1P	Y'_{c1}	Fixed Y-Coordinate (See diagram below)	Inches
	11-20	YC2P	Y'_{c2}		
	21-30	YC3P	Y'_{c3}		
	31-40	YC4P	Y'_{c4}		
	41-50	YC5P	Y'_{c5}		
	51-60	YC6P	Y'_{c6}		
3	1-10	ZC2P	Z'_{c2}	Fixed Z-Coordinate	Inches
	11-20	ZC3P	Z'_{c3}		
	21-30	ZC4P	Z'_{c4}		
	31-40	ZC5P	Z'_{c5}		
	41-50	ZC6P	Z'_{c6}		
4	1-10	PHIC1	ϕ_{c1}	Fixed Phi-Coordinate	Degrees
	11-20	PHIC2	ϕ_{c2}		
	21-30	PHIC3	ϕ_{c3}		
	31-40	PHIC4	ϕ_{c4}		
	41-50	PHIC5	ϕ_{c5}		
	51-60	PHIC6	ϕ_{c6}		

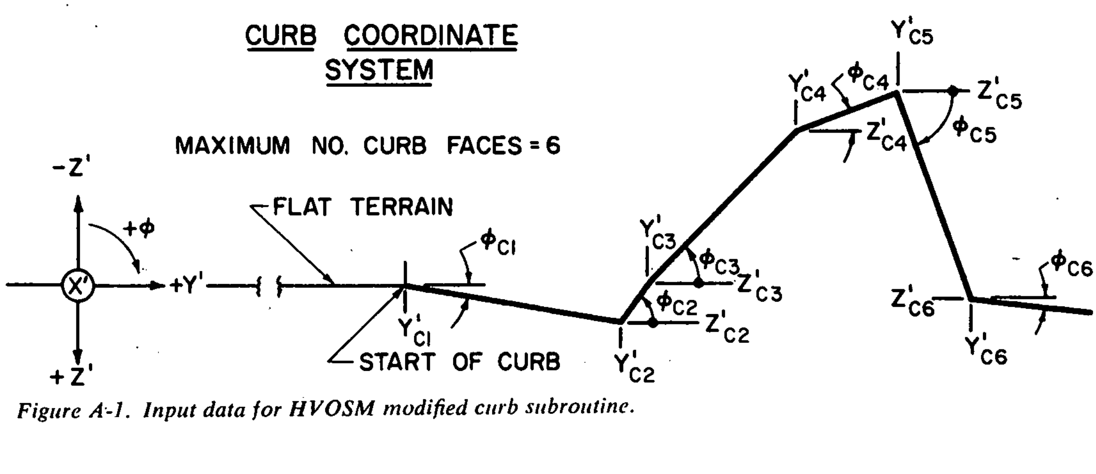


Figure A-1. Input data for HVOSM modified curb subroutine.

used for reading the input data in a proper sequence. The second, third, and fourth IBM cards contain information on the Y'_{ci}, Z'_{ci}, and ϕ_{ci} curb coordinates, respectively.

At the present time, the program is written in a manner that requires the user to supply the curb input data cards even in the absence of a curb. In this case, all four cards are BLANK except for the ICARD integer number 15.

IDEALIZATION OF CURBS

In this study four curbs were investigated. The idealization of the curbs by a series of straight-line segments is shown in Figure A-2. Computer listings of the input data on the four curbs are shown in Figures A-3 through A-6.

A smooth transition from the curb-radial tire subroutine to the terrain-tire subroutine was provided in the runs for curbs Types C, E, and H with a curb rise of 0.1 in. over a lateral runout distance of 5.0 in. as shown in Figures A-3, A-4, and A-5. The modified HVOSM program transfers from the curb-tire subroutine to the terrain-tire subroutine where the curb face has a value of zero. It was found that a lateral runout of 0.1-in. rise over a distance of 5 in. was about the flattest slope for which reasonable results were obtained. Flatter slopes violated the computer transfer controls due to round-off errors. The curb-radial tire subroutine is idealized by radial springs every 4 deg, whereas

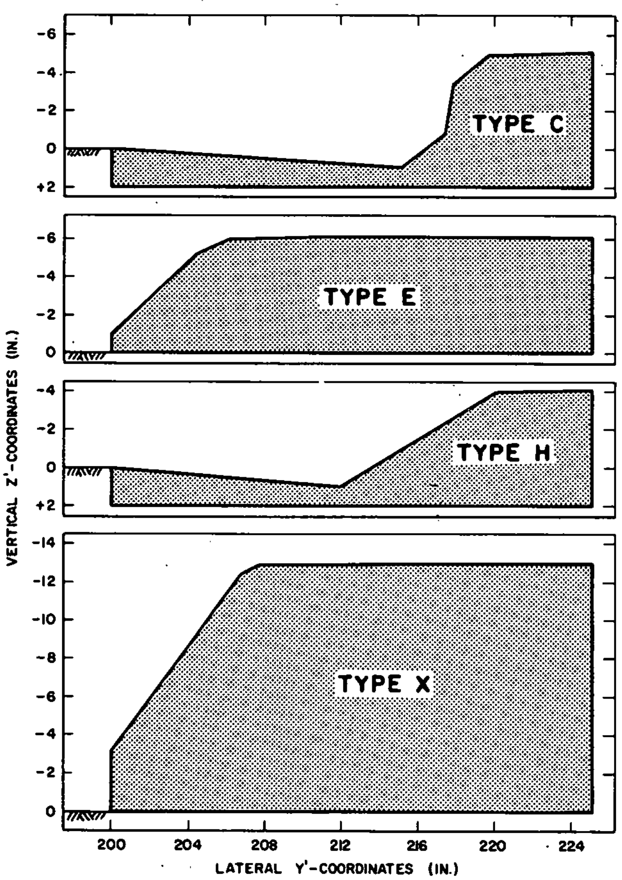


Figure A-2. Idealization of curbs by a series of straight-line segments.

the terrain-tire subroutine is idealized by one radial spring. Hence, the computer run time of the terrain-tire subroutine is considerably less than the curb-tire subroutine.

VEHICLE INPUT DATA

Two 1963 Ford Galaxies differing in weight, inertial properties, suspension properties, and tire properties were used in this study.

The test vehicle, which was of special design for police use, was obtained from CAL. The vehicle weighed 4,200 lb and had a heavy-duty suspension system.

The parameter study vehicle was typical of a standard-design passenger vehicle. The vehicle weighed 3,820 lb and had a suspension system softer than that of the CAL test vehicle. This vehicle also had been used earlier in an NCHRP study by Weaver, et al. (*16*).

Excerpts from the computer printout of the input properties in which the two vehicles differed are shown in Figures A-7 and A-8.

Mass and Inertial Properties

The mass and inertial properties of the two vehicles are shown in Figure A-7. The properties of the parameter study vehicle were obtained from the NCHRP report by Weaver, et al. (*16*). Due to lack of information on the 4,200-lb test vehicle, its mass and inertial properties were determined from the literature presented by Rasmussen, et al. (*17*) of General Motors. His measurements on a number of vehicles using specifically designed test equipment provided the following linear relationships:

$$W_{uf} = 0.040\ W_t + 60$$
$$W_{ur} = 0.067\ W_t + 90$$
$$W_s = W_t - W_{uf} - W_{ur}$$
$$I_{x_s}{}^{cgs} = 0.16\ W_t - 265$$
$$I_{y_t}{}^{cgt} = 1.13\ W_t - 2020$$
$$I_{z_t}{}^{cgt} = 1.26\ W_t - 1750$$

in which

W_{uf} = vehicle front unsprung weight (lb);
W_t = total vehicle weight (lb)
W_t (test vehicle) = 4,200 lb
W_t (parameter vehicle) = 3,820 lb;
W_{ur} = vehicle rear unsprung weight (lb);
W_s = vehicle sprung weight (lb);
$I_{x_s}{}^{cgs}$ = sprung mass roll moment of inertia (slug-ft^2);
$I_{y_t}{}^{cgt}$ = total vehicle pitch moment of inertia (slug-ft^2); and
$I_{z_t}{}^{cgt}$ = total vehicle yaw moment of inertia (slug-ft^2).

An idealization of the HVOSM is shown in Figure A-9 to acquaint the reader with vehicle terminology. The model is idealized as four rigid masses: (a) the sprung (M_S) of the body supported by the springs, (b) both the unsprung masses (M_1 and M_2) of the left and right independent suspension system of the front wheels, and (c) the unsprung mass (M_3) representing the rear axle assembly. The 11 degrees of freedom of the model include translation of the vehicle in three directions measured relative to the fixed coordinate axes system shown in Figure A-1;

***** CURB IMPACT DATA *****

VEHICLE-CURB FRICTION COEFFICIENT (AMUC) = 0.500

FIXED SPACE Y-COORDINATES (INCHES)

YC1P	YC2P	YC3P	YC4P	YC5P	YC6P
200.000	215.000	217.250	217.700	219.550	224.550

FIXED SPACE Z-COORDINATES (INCHES)

ZC2P	ZC3P	ZC4P	ZC5P	ZC6P
0.880	-0.800	-3.450	-5.000	-5.100

FIXED SPACE PHI-COORDINATES (DEGREES)

PHIC1	PHIC2	PHIC3	PHIC4	PHIC5	PHIC6
3.350	-36.750	-80.367	-39.950	-1.150	0.0

Figure A-3. Computer listing of input data for Type C curb.

***** CURB IMPACT DATA *****

VEHICLE-CURB FRICTION COEFFICIENT (AMUC) = 0.800

FIXED SPACE Y-COORDINATES (INCHES)

YC1P	YC2P	YC3P	YC4P	YC5P	YC6P
200.000	200.050	204.400	206.100	211.100	

FIXED SPACE Z-COORDINATES (INCHES)

ZC2P	ZC3P	ZC4P	ZC5P	ZC6P
-1.000	-5.300	-6.000	-6.100	

FIXED SPACE PHI-COORDINATES (DEGREES)

PHIC1	PHIC2	PHIC3	PHIC4	PHIC5	PHIC6
-87.133	-44.667	-22.383	-1.150	0.0	

Figure A-4. Computer listing of input data for Type E curb.

***** CURB IMPACT DATA *****

VEHICLE-CURB FRICTION COEFFICIENT (AMUC) = 0.500

FIXED SPACE Y-COORDINATES (INCHES)

YC1P	YC2P	YC3P	YC4P	YC5P	YC6P
200.000	212.000	220.000	225.000		

FIXED SPACE Z-COORDINATES (INCHES)

ZC2P	ZC3P	ZC4P	ZC5P	ZC6P
1.000	-3.000	-3.100		

FIXED SPACE PHI-COORDINATES (DEGREES)

PHIC1	PHIC2	PHIC3	PHIC4	PHIC5	PHIC6
4.770	-26.570	-1.130	0.0		

Figure A-5. Computer listing of input data for Type H curb.

***** CURB IMPACT DATA *****

VEHICLE-CURB FRICTION COEFFICIENT (AMUC) = 0.500

FIXED SPACE Y-COORDINATES (INCHES)

YC1P	YC2P	YC3P	YC4P	YC5P	YC6P
200.000	200.100	206.700	207.700		

FIXED SPACE Z-COORDINATES (INCHES)

ZC2P	ZC3P	ZC4P	ZC5P	ZC6P
-3.000	-12.500	-13.000		

FIXED SPACE PHI-COORDINATES (DEGREES)

PHIC1	PHIC2	PHIC3	PHIC4	PHIC5	PHIC6
-88.080	-55.220	-26.570	0.0		

Figure A-6. Computer listing of input data for Type X curb.

INERTIAL DATA			TIRE DATA	
MS	= 9.3183	LB.-SEC.**2/IN	KT	1300.000 LB/IN
MUF	= 0.5901	"	SIGMAT	= 3.000
MUR	= 0.9612	"	LAMBDAT	= 10.000
			A0	=4000.000
IX	= 4884.0	LB.-SEC.**2-IN	A1	= 8.400
IY	= 32712.0	"	A2	=3000.000
IZ	= 42504.0	"	A3	= 1.710
IXZ	=-192.000	"	A4	=4200.000
IR	= 600.00	"	AMU	= 0.800
G	= 386.400	IN/SEC.**2	OMEGT	= 1.000

TEST VEHICLE

INERTIAL DATA			TIRE DATA	
MS	= 8.4402	LB.-SEC.**2/IN	KT	1098.000 LB/IN
MUF	= 0.5507	"	SIGMAT	= 3.000
MUR	= 0.8952	"	LAMBDAT	= 10.000
			A0	=4400.000
IX	= 6200.0	LB.-SEC.**2-IN	A1	= 8.276
IY	= 34400.0	"	A2	=2900.000
IZ	= 36000.0	"	A3	= 1.780
IXZ	=-192.000	"	A4	=3900.000
IR	= 600.00	"	AMU	= 0.800
G	= 386.400	IN/SEC.**2	OMEGT	= 1.000

PARAMETER STUDY VEHICLE

Figure A-7. Computer listing of input data for vehicle inertial and tire properties.

SUSPENSION DATA					
KF	= 131.000	LB./IN.	LAMBDAF	= 0.500	
KR	= 192.000	LB./IN.	LAMBDAR	= 0.500	
CF'	= 55.000	LBS.	OMEGAF	= 3.000	INCHES
CR'	= 50.000	LBS.	OMEGAR	= 4.000	INCHES
EPSILONF	= 0.001	IN./SEC.	TS	= 46.500	INCHES
EPSILONR	= 0.001	IN./SEC.	RR	= 61900.0	LB-IN/RAD
CF	= 3.500	LB-SEC/IN	RF	=266000.0	LB-IN/RAD
CR	= 3.900	LB-SEC/IN	KRS	= 0.070	ROLL STEER COEFF.
AKFC	= 300.000	LB/IN	AKRC	= 300.000	LB/IN
AKFCP	= 2.000	LB/IN3	AKRCP	= 2.000	LB/IN3
OMEGFC	= -3.000	IN	OMEGRC	= -4.000	IN
AKFE	= 300.000	LB/IN	AKRE	= 300.000	LB/IN
AKFEP	= 2.000	LB/IN3	AKREP	= 2.000	LB/IN3
OMEGFE	= 5.000	IN	OMEGRE	= 4.500	IN

TEST VEHICLE

SUSPENSION DATA					
KF	= 100.000	LB./IN.	LAMBDAF	= 0.500	
KR	= 105.000	LB./IN.	LAMBDAR	= 0.500	
CF'	= 30.000	LBS.	OMEGAF	= 3.000	INCHES
CR'	= 45.000	LBS.	OMEGAR	= 4.000	INCHES
EPSILONF	= 0.001	IN./SEC.	TS	= 46.500	INCHES
EPSILONR	= 0.001	IN./SEC.	RR	= 32500.0	LB-IN/RAD
CF	= 3.500	LB-SEC/IN	RF	= 98500.0	LB-IN/RAD
CR	= 3.900	LB-SEC/IN	KRS	= 0.070	ROLL STEER COEFF.
AKFC	= 300.000	LB/IN	AKRC	= 300.000	LB/IN
AKFCP	= 2.000	LB/IN3	AKRCP	= 2.000	LB/IN3
OMEGFC	= -3.000	IN	OMEGRC	= -4.000	IN
AKFE	= 300.000	LB/IN	AKRE	= 300.000	LB/IN
AKFEP	= 2.000	LB/IN3	AKREP	= 2.000	LB/IN3
OMEGFE	= 5.000	IN	OMEGRE	= 4.500	IN

PARAMETER STUDY VEHICLE

Figure A-8. Computer listing of input data for vehicle suspension.

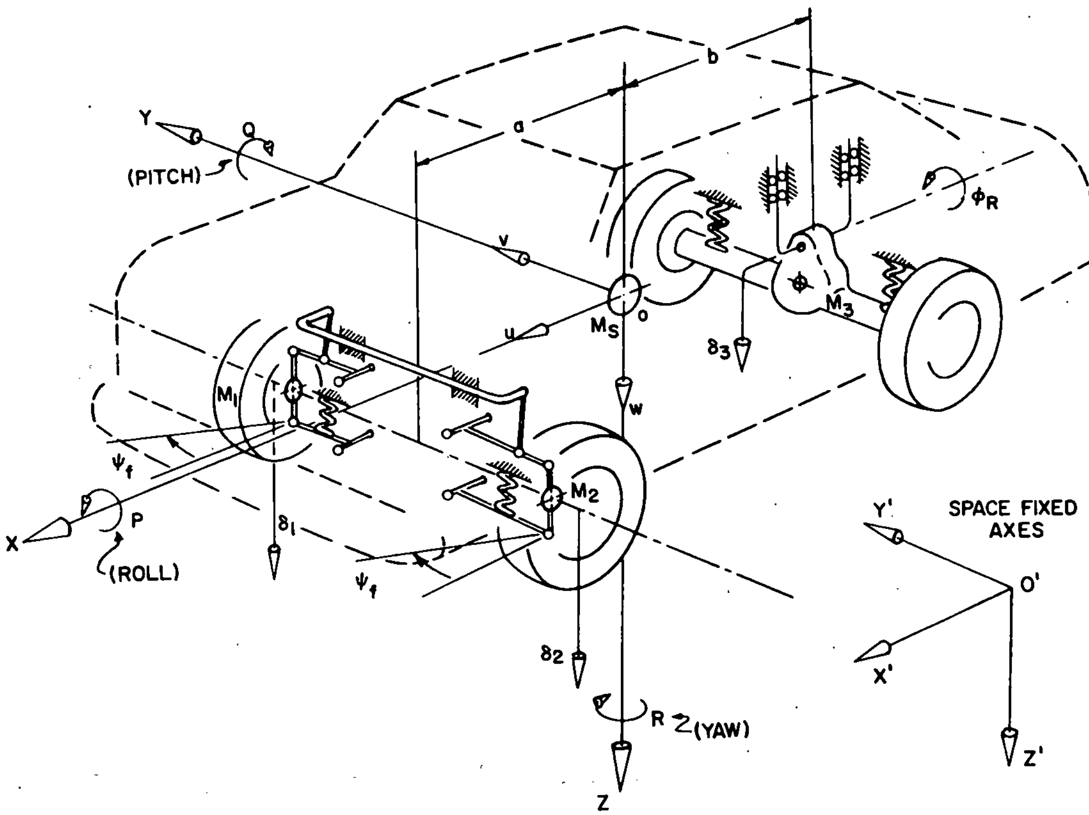


Figure A-9. Idealization of the HVOSM vehicle. Source: (2).

rotation about the three coordinate axes of the vehicle; independent displacement of each front wheel suspension system; suspension displacement and rotation of the rear axle assembly; and steer of the front wheels. A more detailed discussion of the HVOSM model can be found elsewhere (*15, 18, 19*).

Tire Properties

The tire properties of the two vehicles are shown in Figure A-7. The type of tires used on the test vehicle were Uniroyal G78-14 bias-belted, polyester-fiberglass mounted on 6-in. rims. The type of tires used on the parameter study vehicle were Sears Super-Tread.

The reader is referred to the HVOSM documentation report by Young, et al. (*19*) for the definition of the Sears Super-Tread tire parameters and to a CAL report (*20*) for the Uniroyal tire parameters.

Suspension Properties

The input suspension properties of the test vehicle and the parameter study vehicle are shown in Figure A-8. As mentioned earlier, the suspension system of the test vehicle was stiffer than that of the parameter study vehicle.

The two vehicles differed in: (a) the suspension load-deflection characteristics of the front (KF) and rear (KR) wheels; and (b) the viscous damping suspension coefficients for the front (CF′) and rear (CR′) wheels.

The reader is referred to the HVOSM documentation report by Young, et al. (*19*) for the definitions of the remaining suspension parameters in Figure A-8.

MODIFIED HVOSM SUBROUTINES

Increasing the number of curb faces from *two* in the previous HVOSM to *six* in this study required changes and additions to five subroutines. The five subroutines were:

1. INPUT—This subroutine reads in the input formulated in Figure A-1.
2. IDOUT—This subroutine writes out the input data.
3. CNSTNT—This subroutine contains constants and conversion factors.
4. VGORNT—This subroutine, called the "Vehicle Ground Orientation Subroutine," calls the "Curb Impact Subroutine (CRBIMP)" whenever a wheel is within some defined curb boundaries.
5. CRBIMP—This subroutine is called the "Curb Impact Subroutine." It was within this subroutine that the major modifications were made. A listing of the modified curb subroutine follows for those who are interested in the use of the HVOSM.

MODIFIED CRBIMP SUBROUTINE

The modified portions of the curb subroutine can be identified by the absence of the right-hand statement numbers designated "CRMP 0, CRMP 1, CRMP 2, and so on.

```
C
C      SINGLE VEHICLE ACCIDENT SIMULATION WITH CURB IMPACT - CRBIMP       CRMP   0
       SUBROUTINE CRBIMP(I)                                               CRMP   1
       COMMON/INPT/PHIO,THETAO,PSIO,PO,QO,RO,XCOP,YCOP,ZCOP,UO,VO,WO,A,B,CRMP   2
     1              DEL1O,DEL2O,DEL3O,PHIRO,DEL1OD,DEL2OD,DEL3OD,PHIROD,TFCRMP   3
     2             ,TR,ZF,ZR,RHO,RW,AKT,SIGT,XLAMT,A1,A2,A3,AKRS,AMU,XMUR,CRMP   4
     3              XMS,XMUF,XIX,XIY,XIZ,XIXZ,CF,AKF,XLAMF,OMEGF,CFP,EPSF,CRMP   5
     4              RF,CR,AKR,XLAMR,OMEGR,CRP,EPSR,RR,TS,THMAX,DTCOMP,TO,  CRMP   6
     5              T1,DTCMP1,DTPRNT,MODE,EBAR,EM,AAA,HMAX,HMIN,BET,G,     CRMP   7
     6              HED(36),DADE(3),XIR,X1,Y1,Z1,X2,Y2,Z2,PHIC(50),DELB,   CRMP   8
     7              DELE,DDEL,NDEL,PSIF(50),TQF(50),TQR(50),TB,TE,TINCR,   CRMP   9
     8              XBDRY(10),YBDRY(10),ZGP(21,21),THG(21,21),PHIG(21,21),CRMP  10
     9              XB,XE,XINCR,NX,YB,YE,YINCR,NY,NBX,NBY,UVWMIN,PQRMIN    CRMP  11
       COMMON/INPT1/YC1P,YC2P,ZC2P,DELTC,PHIC1,PHIC2,AMUC,FJP(35),XIPS,   CRMP  12
     1              CPSP,OMGPS,AKPS,EPSPS,XPS,RWHJB,RWHJE,DRWHJ,INDCRB,   CRMP  13
     2              PSIFIO,PSIFDO                                          CRMP  14
       COMMON/INPT5/ YC3P, YC4P, YC5P, YC6P, YCLP,
     1               ZC3P, ZC4P, ZC5P, ZC6P, ZCLP,
     2               PHIC3, PHIC4, PHIC5, PHIC6, NCRBSL,
     3               TANPC3, TANPC4, TANPC5, TANPC6, TANPCL,
     4               PHIC3R, PHIC4R, PHIC5R, PHIC6R, PHICLR,
     5               YCMP(6), ZCMP(6), PHICM(6)
       COMMON /INTG/NEQ,T,DT,VAR(50),DER(50)                              CRMP  15
       COMMON /DIMV/X1P,X2P,X3P,X4P,Y1P,Y2P,Y3P,Y4P,Z1P,Z2P,Z3P,Z4P,PHI1,CRMP  16
     1              PHI2,PHI3,PHI4,PSI1,PSI2,PSI3,PSI4,CAYW(4),CBYW(4),   CRMP  17
     2              CGYW(4),ZPGI(4),THGI(4),PHGI(4),CPG(4),SPG(4),CTG(4),CRMP  18
     3              STG(4),CAGZ(4),CBGZ(4),CGGZ(4),D1(4),D2(4),D3(4),     CRMP  19
     4              XLM1(4),XLM2(4),XLM3(4),AMTX(3,3),CMTX(3,4),XGPP(4),  CRMP  20
     5              YGPP(4),ZGPP(4),DMATX(10,11),DELTA(4),CAR(4),CBR(4),  CRMP  21
     6              CGR(4),FR(4),HI(4),FC(4),TI(4),AX(4),BX(4),CX(4),     CRMP  22
     7              CTXG(4),UG(4),STXG(4),AY(4),BY(4),CY(4),CPYG(4),      CRMP  23
     8              SPYG(4),VG(4),PSIIP(4),PHICI(4),CAC(4),CBC(4),CGC(4),CRMP  24
     9              FCXU(4),FCYU(4),FCZU(4),FS(4),CAXW(4),CBXW(4),CGXW(4)CRMP  25
       COMMON /DIMV/AS(4),BS(4),CS(4),CAS(4),CBS(4),CGS(4),BETP(4),       CRMP  26
     1              BETBR(4),FSXU(4),FSYU(4),FSZU(4),FRXU(4),FRYU(4),     CRMP  27
     2              FRZU(4),FXU(4),FYU(4),FZU(4),SI(4),F1FI(2),F1RI(2),   CRMP  28
     3              F2FI(2),F2RI(2),CAH(4),CBH(4),CGH(4)                  CRMP  29
       COMMON /COMP/SUMM,THETN,PHIN,PSIN,PI,RAD,GAM1,GAM2,GAM3,GAM4,GAM5,CRMP  30
     1              GAM6,GAM7,GAM8,GAM9,THETT,PHIT,PSIT,A12,A23,ZRO,TRO2,CRMP  31
     2              TFO2,TIZ,RHO2,RHOMUR,AMUF,BMUR,ZPR,TM4,RHMR2,AO2APB,  CRMP  32
     3              BO2APB,RFTF,TSO2,RRTS,BROMUR,XMUFO2,AXMFO2,XMTFO4,    CRMP  33
     4              XIZR,RTR,RHMR2I,XIXP,XIZP,XIXZP,XIYZP,D1PD2,D1MD2,    CRMP  34
     5              ZRD3,ZRD3R,ZFD3R,ZFD12,TIZ2,TG61,DD1P2,DD1M2,RPR,PHRPCRMP  35
     6             ,TANTP,SPHTP,CPHTP,SECTP,SFXS,SFYS,SFZS,SNPS,SNTS,     CRMP  36
     7              SNPSS,TPR,CAY,CBY,CGY,CAX,CBX,CGX,SFYU,SFXU,SFYUF,    CRMP  37
     8              SFYUR,SFZU,COSTH,SINTH,COSPS,SINPS,COSPH,SINPH,ANG1,  CRMP  38
     9              ANG2,CPHI,SPHI,CPSI,SPSI,P1,P7,P3,P4,P5,P6,TX,TY,TZ   CRMP  39
       COMMON /COMP/TRH,DISTX,DISTY,DISTD,DISTS,D21,ZETA4,ZETA4D,ZETA3,   CRMP  40
     1              ZETA3D,SFZ1,SNPU,SNTU,HCGH1,HCGH2,HCGH3,HCGH4,TERM1,  CRMP  41
     2              TERM2,SNPSU,SNPR,HCBH1,HCBH2,HCBH3,HCBH4,HCAH1,HCAH2,CRMP  42
     3              HCAH3,HCAH4,UQ,WP,UR,QR,VP,PR,P2,Q2,R2,VR,WQ,PQ,PHIR2CRMP  43
     4             ,PHIRD2,RPHRD,GCTH,GSTH,GCTSP,GCTCP,XXX,YYY,IX,IY,XX1,CRMP  44
     5              XX2,YY1,YY2,THG1,THG2,PHG1,PHG2,ZZ1,ZZ2,LLL           CRMP  45
       COMMON /COMPN/ OMT2M1,FRSP(4),FRCP(4),OMEGT,ICBHIT,JCBHIT,         CRMP  46
     1                DPSINT,TANPC1,TANPC2,PHIC1R,PHIC2R,AMUCMP,PHI1D,    CRMP  47
     2                PHI2D,LCB1(4),LCB2(4),IHIT,AJMTX(3,3),BMTX(3,3),    CRMP  48
     3                SFRX(4),SFRY(4),SFRZ(4),T1PSI,T2PSI,XMU             CRMP  49
       COMMON/ADTNL/U1,U2,U3,U4,V1,V2,V3,V4,W1,W2,W3,W4,XTRA(300)         CRMP  50
       DIMENSION XP(4),YP(4),ZP(4),PHII(4),PSII(4),UI(4),VI(4),WI(4)      CRMP  51
       EQUIVALENCE (XP,X1P),(YP,Y1P),(ZP,Z1P),(PHII,PHI1),(PSII,PSI1),    CRMP  52
     1             (UI,U1),(VI,V1),(WI,W1)                                CRMP  53
       EQUIVALENCE (U,VAR(1)),(V,VAR(2)),(W,VAR(3)),(P,VAR(4)),(Q,VAR(5))CRMP  54
     1            ,(R,VAR(6)),(DEL1,VAR(7)),(DEL1D,VAR(8)),(DEL2,VAR(9)),CRMP  55
     2             (DEL2D,VAR(10)),(DEL3,VAR(11)),(DEL3D,VAR(12)),        CRMP  56
     3             (PHIR,VAR(13)),(PHIRD,VAR(14)),(THETTP,VAR(15)),       CRMP  57
     4             (PHITP,VAR(16)),(PSITP,VAR(17)),(XCP,VAR(18)),         CRMP  58
     5             (YCP,VAR(19)),(ZCP,VAR(20)),(PSIFI,VAR(21)),           CRMP  59
     6             (PSIFID,VAR(22))                                       CRMP  60
```

```
      EQUIVALENCE (DU,DER(1)),(DV,DER(2)),(DW,DER(3)),(DP,DER(4)),      CRMP  61
     1            (DQ,DER(5)),(DR,DER(6)),(DDEL1,DER(7)),(DDEL1D,DER(8))CRMP  62
     2           ,(DDEL2,DER(9)),(DDEL2D,DER(10)),(DDEL3,DER(11)),      CRMP  63
     3            (DDEL3D,DER(12)),(DPHIR,DER(13)),(DPHIRD,DER(14)),    CRMP  64
     4            (DTHTTP,DER(15)),(DPHITP,DER(16)),(DPSITP,DER(17)),   CRMP  65
     5            (DXCP,DER(18)),(DYCP,DER(19)),(DZCP,DER(20)),         CRMP  66
     6            (DPSIFI,DER(21)),(DDPSFI,DER(22))                     CRMP  67
      DIMENSION YCIP(2)                                                 CRMP  68
      EQUIVALENCE (YCIP,YC1P)                                           CRMP  69
      EQUIVALENCE (XIYP,XTRA(1)),(SPHIC,XTRA(2)),(CPHIC,XTRA(3))        CRMP  70
      LOGICAL LCB1,LCB2                                                 CRMP  71
    1 SNPSI = SIN(PSII(I))                                              CRMP  72
      CSPSI = COS(PSII(I))                                              CRMP  73
      SNPHI = SIN(PHII(I))                                              CRMP  74
      CSPHI = COS(PHII(I))                                              CRMP  75
      SFRX(I) = 0.0                                                     CRMP  76
      SFRY(I) = 0.0                                                     CRMP  77
      SFRZ(I) = 0.0                                                     CRMP  78
      TTAJ21 = CSPHI * SNPSI
      TTAJ31 = SNPHI * SNPSI
      AJMTX(1,2) = -SNPSI
      AJMTX(2,2) = CSPHI * CSPSI
      AJMTX(3,2) = SNPHI * CSPSI
      XJ = -26.0*RAD
    2 DO 11 J=1,53
      THTJ = 4.0*XJ
      STJ = SIN(THTJ)
      CTJ = COS(THTJ)
      AJMTX(1,1) = CTJ * CSPSI
      AJMTX(2,1) = TTAJ21*CTJ + SNPHI*STJ
      AJMTX(3,1) = TTAJ31*CTJ - CSPHI*STJ
      AJMTX(1,3) = CSPHI*STJ
      AJMTX(2,3) = TTAJ21*STJ - SNPHI*CTJ
      AJMTX(3,3) = TTAJ31*STJ + CSPHI*CTJ
    3 DO 8  K=1,3                                                       CRMP  93
    4 DO 7  L=1,3                                                       CRMP  94
      BMTX(K,L) = 0.0                                                   CRMP  95
    5 DO 6  M=1,3                                                       CRMP  96
      BMTX(K,L) = BMTX(K,L)+AMTX(K,M)*AJMTX(M,L)                        CRMP  97
    6 CONTINUE                                                          CRMP  98
    7 CONTINUE                                                          CRMP  99
    8 CONTINUE                                                          CRMP 100
C
      HJ = -ZP(I)/BMTX(3,3)
      IF ( HJ .LT. 0.0 .OR. HJ .GE. RW ) GO TO 800
      YJP = YP(I) + BMTX(2,3)*HJ
      IF ( YJP .LT. YC1P ) GO TO 203
  800 HJ = (-ZP(I) + (YP(I) - YC1P)*TANPC1 ) /
     1 ( BMTX(3,3) - BMTX(2,3)*TANPC1 )
      IF ( HJ .LT. 0.0 .OR. HJ .GE. RW ) GO TO 805
      YJP = YP(I) + BMTX(2,3)*HJ
      ZJP = ZP(I) + BMTX(3,3)*HJ
      IF ( YJP .GE. YC1P .AND. YJP .LE. YC2P .AND.
     1 (ABS(ZJP) .LE. ABS(ZC2P)) .AND.
     2 (SIGN(1.0,ZJP) .EQ. SIGN(1.0,ZC2P))) GO TO 204
  805 HJ = ( ZC2P - ZP(I) + (YP(I) - YC2P)*TANPC2 ) /
     1 ( BMTX(3,3) - BMTX(2,3)*TANPC2 )
      IF ( HJ .LT. 0.0 .OR. HJ .GE. RW ) GO TO 810
      YJP = YP(I) + BMTX(2,3)*HJ
      ZJP = ZP(I) + BMTX(3,3)*HJ
      IF ( YJP .GT. YC2P .AND. YJP .LE. YC3P .AND.
     1 (ABS(ZJP) .LE. ABS(ZC3P)) .AND.
     2 (SIGN(1.0,ZJP) .EQ. SIGN(1.0,ZC3P))) GO TO 204
  810 IF ( NCRBSL .EQ. 2 ) GO TO 10
      HJ = ( ZC3P - ZP(I) + ( YP(I) - YC3P)*TANPC3 ) /
```

```
     1 ( BMTX(3,3) - BMTX(2,3)*TANPC3 )
      IF ( HJ .LT. 0.0 .OR. HJ .GE. RW ) GO TO 815
      YJP = YP(I) + BMTX(2,3)*HJ
      ZJP = ZP(I) + BMTX(3,3)*HJ
      IF ( YJP .GT. YC3P .AND. YJP .LE. YC4P .AND.
     1 ( ABS(ZJP) .LE. ABS(ZC4P)) .AND.
     2 ( SIGN(1.0,ZJP) .EQ. SIGN(1.0,ZC4P))) GO TO 204
  815 IF ( NCRBSL .EQ. 3 ) GO TO 10
      HJ = ( ZC4P - ZP(I) + ( YP(I) - YC4P )*TANPC4 ) /
     1 ( BMTX(3,3) - BMTX(2,3)*TANPC4 )
      IF ( HJ .LT. 0.0 .OR. HJ .GE. RW ) GO TO 820
      YJP = YP(I) + BMTX(2,3)*HJ
      ZJP = ZP(I) + BMTX(3,3)*HJ
      IF ( YJP .GT. YC4P .AND. YJP .LE. YC5P .AND.
     1 (ABS(ZJP) .LE. ABS(ZC5P)) .AND.
     2 (SIGN(1.0,ZJP) .EQ. SIGN(1.0,ZC5P))) GO TO 204
  820 IF ( NCRBSL .EQ. 4 ) GO TO 10
      HJ = ( ZC5P - ZP(I) + ( YP(I) - YC5P)*TANPC5 ) /
     1 ( BMTX(3,3) - BMTX(2,3)*TANPC5 )
      IF ( HJ .LT. 0.0 .OR. HJ .GE. RW ) GO TO 825
      YJP = YP(I) + BMTX(2,3)*HJ
      ZJP = ZP(I) + BMTX(3,3)*HJ
      IF ( YJP .GT. YC5P .AND. YJP .LE. YC6P .AND.
     1 (ABS(ZJP) .LE. ABS(ZC6P)) .AND.
     2 ( SIGN(1.0,ZJP) .EQ. SIGN(1.0,ZC6P))) GO TO 204
  825 IF ( NCRBSL .EQ. 5 ) GO TO 10
      HJ = ( ZC6P - ZP(I) + (YP(I) - YC6P)*TANPC6 ) /
     1 ( BMTX(3,3) - BMTX(2,3)*TANPC6 )
      IF ( HJ .LT. 0.0 .OR. HJ .GE. RW ) GO TO 10
      YJP = YP(I) + BMTX(2,3)*HJ
      IF ( YJP .LT. YC6P ) GO TO 10
  203 ZJP = ZP(I) + BMTX(3,3)*HJ
  204 XJP = XP(I) + BMTX(1,3)*HJ
      CAJ = (XP(I)-XJP)/HJ
      CBJ = (YP(I)-YJP)/HJ
      CGJ = (ZP(I)-ZJP)/HJ
      CALL INTRPL(FJP,RWHJB,RWHJE,DRWHJ,RW-HJ,FJ)
      SFRX(I) = SFRX(I)+FJ*CAJ
      SFRY(I) = SFRY(I)+FJ*CBJ
      SFRZ(I) = SFRZ(I)+FJ*CGJ
   10 XJ = XJ+RAD
   11 CONTINUE
      FR(I) = SQRT(SFRX(I)**2+SFRY(I)**2+SFRZ(I)**2)
      IF(FR(I).NE.0.0)GO TO 110
      CAR(I) = 0.0
      CBR(I) = 0.0
      CGR(I) = 0.0
      HI(I) = RW
      RETURN
  110 CAR(I) = -SFRX(I)/FR(I)
      CBR(I) = -SFRY(I)/FR(I)
      CGR(I) = -SFRZ(I)/FR(I)
      HI(I) = RW-FR(I)/AKT
      IF(HI(I).GT.RW-SIGT) GO TO 111
      HI(I) = RW-(FR(I)/AKT+SIGT*(XLAMT-1.0))/XLAMT
C
  111 TYGP = YP(I) + HI(I)*CBR(I)
      PHGI(I) = 0.0
      IF ( TYGP .LE. YC1P ) GO TO 12
      IF ( TYGP .GT. YC1P .AND. TYGP .LE. YC2P ) GO TO 900
      GO TO 905
  900 PHGI(I) = PHIC1R
      GO TO 12
```

```
  905 IF ( NCRBSL .EQ. 2 ) GO TO 970
      IF ( TYGP .GT. YC2P .AND. TYGP .LE. YC3P ) GO TO 910
      GO TO 915
  910 PHGI(I) = PHIC2R
      GO TO 12
  915 IF ( NCRBSL .EQ. 3 ) GO TO 970
      IF ( TYGP .GT. YC3P .AND. TYGP .LE. YC4P ) GO TO 920
      GO TO 925
  920 PHGI(I) = PHIC3R
      GO TO 12
  925 IF ( NCRBSL .EQ. 4 ) GO TO 970
      IF ( TYGP .GT. YC4P .AND. TYGP .LE. YC5P ) GO TO 930
      GO TO 935
  930 PHGI(I) = PHIC4R
      GO TO 12
  935 IF ( NCRBSL .EQ. 5 ) GO TO 970
      IF ( TYGP .GT. YC5P .AND. TYGP .LE. YC6P ) GO TO 940
      GO TO 970
  940 PHGI(I) = PHIC5R
      GO TO 12
  970 PHGI(I) = PHICLR
C
   12 TCI = CAR(I)*CBYW(I) - CBR(I)*CAYW(I)
      TAI = CBR(I)*CGYW(I) - CGR(I)*CBYW(I)
      TBI = CGR(I)*CAYW(I) - CAR(I)*CGYW(I)
      CPG(I) = COS(PHGI(I))
      SPG(I) = SIN(PHGI(I))
      TERM3 = TBI*SPG(I)
      TERM4 = TCI*CPG(I)
      DN1 = TAI * (TERM3 - TERM4)
      DN2 = -TBI*TERM4 - (TAI**2 + TCI**2)*SPG(I)
      DN3 = (TAI**2 + TBI**2)*CPG(I) + TCI*TERM3
      TERM5 = SQRT(DN1**2 + DN2**2 + DN3**2)
      SPG(I) = (-DN2/TERM5)
      PHGI(I) = ARSIN(SPG(I))
      CPG(I) = COS(PHGI(I))
      THGI(I) = ATAN(DN1/DN3)
      TERM6 = SQRT(DN1**2 + DN3**2)
      CTG(I) = DN3/TERM6
      STG(I) = DN1/TERM6
      ZGPP(I) = ZP(I) + HI(I)*CGR(I)
      RETURN
      END
```

APPENDIX B

FULL-SCALE TESTS

INTRODUCTION

Eighteen full-scale tests were conducted to obtain field data for correlation with the HVOSM predictions. The tests consisted of a series of nine impacts each on two curb configurations, each series including 30-, 45-, and 60-mph impacts at 5-, 12.5-, and 20-deg approach angles. The vehicle in each test was driven by a professional test driver. Descriptions of the curb configurations, the test vehicle and its equipment, and the test procedure follow.

CURB CONFIGURATIONS

Although many curb types are used, an investigation of highway design manuals from a majority of the states revealed that two or three typical cross-sections are more widely used than most. In accordance with the AASHTO Blue Book, *A Policy on Geometric Design of Rural Highways* (*1*), Type E curbs and those similar but with slight modifications are widely used in locations where vehicle mounting is expected or desired. AASHTO Type C curbs (*1*), depending on heights and radii selected, are used at locations where mounting may or may not be expected or desired. The Blue Book designates Type C curb as "mountable" but states that a similar type having a vertical face, ½-in. radii, and a 6-in. height would be considered a "barrier" curb. Many states use a Type C curb with 6-in. height and 2-in., or even 3-in., radii as a barrier curb where vehicle mounting is not desired.

Curbs of Types C and E were selected for full-scale testing because they represent the most widely used cross-sections, and the locations at which they are generally used represent different desired operational aspects. The tests were conducted to provide data to validate HVOSM predictions and to observe actual vehicle behavior under various impact conditions.

The geometry of the test curbs is shown in Figure B-1. Both Types C and E curb and gutter sections 100 ft long were placed adjacent to an existing concrete pavement, and the area behind the test curb sections was backfilled and compacted to the elevation of the top of the curb for a distance of approximately 100 ft to provide a vehicle recovery area.

Both concrete test curbs were poured in place on a 3-in. sand base. Three No. 4 reinforcing bars were placed longitudinally in each 100-ft curb section, as shown in Figure B-1. The curb and gutter sections were not doweled to the existing pavement.

The three encroachment paths (5, 12.5, and 20 deg) for each curb section were marked on the pavement with 4-in. white pavement marking tape to guide the driver during his approach (see Fig. 3). The impact point was constant for all tests at each curb.

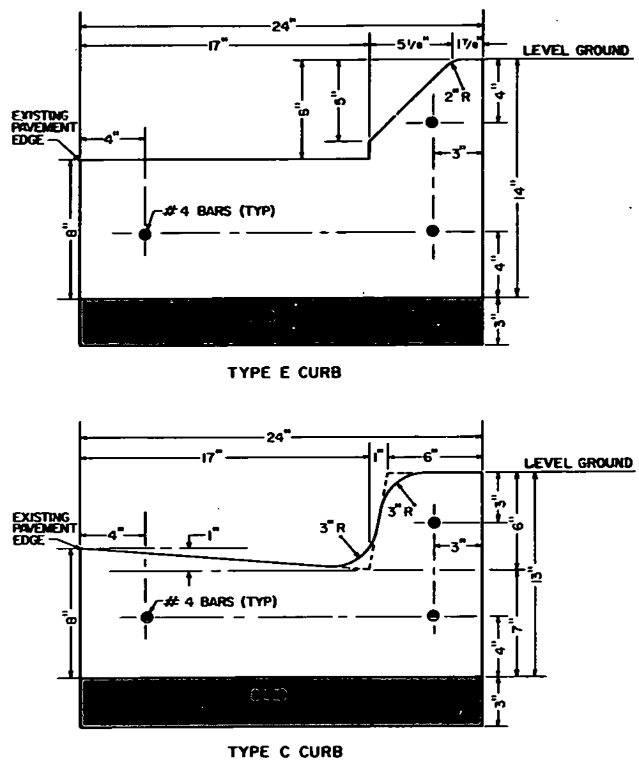


Figure B-1. Geometry of test curbs Types C and E.

TEST VEHICLE

A 1963 Ford four-door sedan with heavy-duty suspension was used for all curb tests. This automobile, owned by the Federal Highway Administration, was used by Cornell Aeronautical Laboratories (CAL) for validation testing during the development of the HVOSM (*15*). It has been used in several validation studies of HVOSM at both the Texas Transportation Institute (TTI) and CAL because it has the required vehicle characteristics. It is representative of the 3,500- to 4,500-lb automobile (having similar distribution of mass and dimensions, such as wheelbase, length, and width) and can be assumed to respond dynamically in a manner similar to other automobiles of this weight and size class.

The test vehicle was modified from stock configuration only to the degree necessary to install instrumentation equipment and to protect the driver and equipment. The rear seat was removed to install recording instrumentation, and the front bench seat was replaced by a bucket seat to provide maximum support for the test driver. A light-frame roll bar was installed to protect the driver. For additional driver protection, the windshield and side glass were removed and replaced by heavy wire mesh.

After modification and installation of the instrumentation equipment, the vehicle was weighed to determine the center of gravity in the longitudinal and lateral axes. The vertical location of the center of gravity was assumed to be the same position as previously reported (*15*). The weight of the test vehicle was 4,200 lb. Vehicle dimensions and camera reference target locations are shown in Figure B-2.

INSTRUMENTATION

Although it was expected that accelerations would be small during impact, three accelerometers were mounted in a cluster near the vehicle's center of gravity to measure longitudinal, lateral, and vertical accelerations (Fig. B-3). The accelerations cluster was located at the intersection of the longitudinal and lateral center of gravity axes and approximately 7 in. below the center of gravity height reported by CAL (*15*). A tri-axes recording Impactograph was also installed on the floor to provide back-up accelerations data in case of primary equipment failure.

Of primary concern were the vehicle's speed, orientation, attitude, and position with respect to the curb face during and after impact. These can best be determined from analysis of high-speed movie film. Two high-speed movie cameras were used for data acquisition purposes; one was

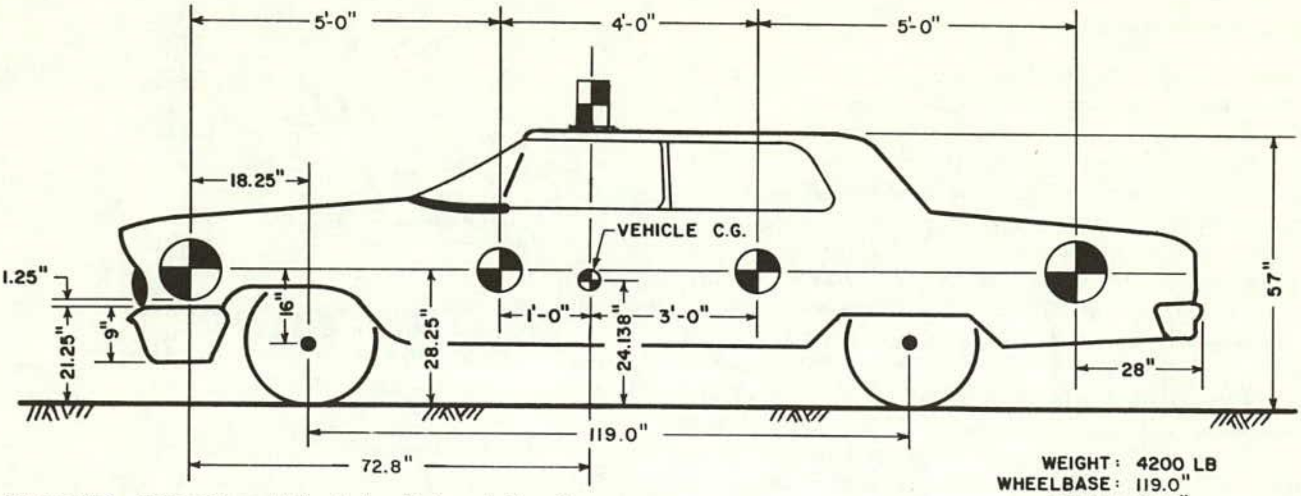


Figure B-2. Dimensions of the test vehicle and its reference targets.

Figure B-3. Test vehicle equipped for curb impact tests.

placed on a line extending from the curb face, and the other perpendicular to the curb face behind the point of impact. In addition, the two documentary movie cameras used for general film coverage were located such that vehicle position could be determined from the documentary film if one of the high-speed cameras became inoperable. Camera positions are shown in Figure B-4. Four targets were mounted on each side of the test vehicle, two were rear-mounted, and one on the roof of the test vehicle (Fig. A-2). These targets served as reference points by which means vehicle motion was determined from the high-speed film analysis (data are presented in Appendix C).

TEST PROCEDURE

In all 18 tests, the test vehicle approached the test curb at a scheduled angle and speed in a straight path delineated with white pavement tape and outlined with traffic cones. (Fig. B-5).

All tests were conducted in a "hands-off" steering mode to minimize the influence of the driver on the vehicle. Once the driver had accelerated to the desired speed, he removed his hands from the steering wheel immediately prior to impacting the curb. Manual steering control was not regained until the vehicle had stabilized after impact. Vehicle path, therefore, was dependent only on the wheel forces induced by the curb and terrain behind the curb.

The test sequence (see Table 2) began with the less severe Type E curb tests in order to permit the maximum data acquisition before working up to the steep Type C curb tests, which would make vehicle repairs necessary.

Certain features of the test procedure and vehicle encroachment conditions are discussed in the following.

Vehicle Approach Speed

Although the test vehicle was equipped with a calibrated speedometer, small deviations from scheduled approach speed were expected. In all but six of the tests, the difference between actual and scheduled speed was less than 3 mph, with many being less than 1 mph. To account for some loss of speed while he was making necessary final

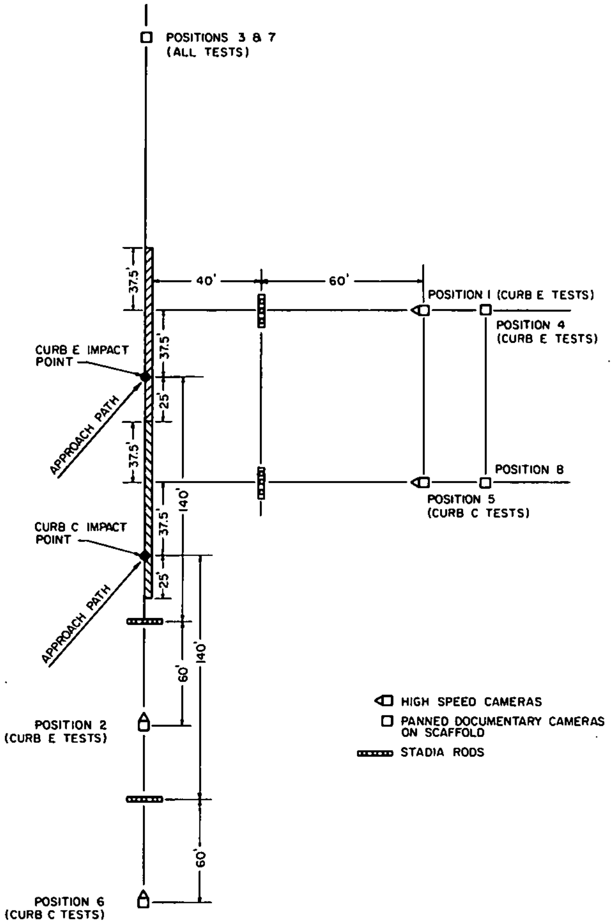


Figure B-4. Diagram of test course and locations of cameras.

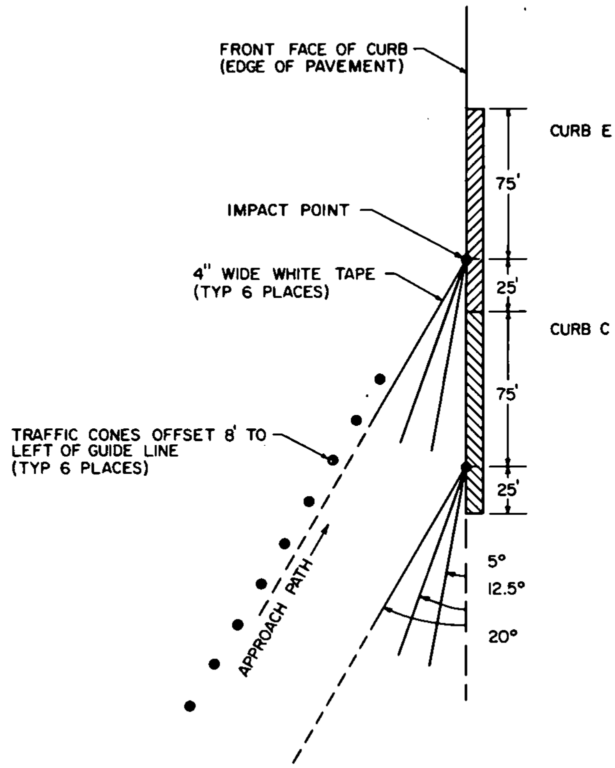


Figure B-5. Diagram of vehicle encroachment angles.

angle corrections just prior to impact, the driver usually maintained a slightly higher than scheduled test speed during his approach. The actual speeds (see Table 2) were determined from the high-speed film analysis and were used as input for the HVOSM validation. These speeds represent an average speed computed over the 14-ft distance between the two 12-in. reference targets from the instant the right front wheel contacted the curb.

Vehicle Approach Angle

The driver started his approach approximately 1,000 ft from the desired impact point. Because the straight approach path was well defined with white tape and traffic cones, the driver experienced no difficulty in achieving the scheduled approach angle or in impacting the curb at the desired point. The approach angles (see Table 2) determined from the film analysis (Appendix C) agreed quite closely with the intended angles.

Vehicle Accelerations

Peak vertical accelerations measured from the accelerometer traces are given in Table 2. Accelerations less than 0.5 g were not included in the summary because the linewidth of the visicorder trace is of this magnitude. The vertical accelerations were much greater than the lateral and longitudinal accelerations and, therefore, the latter two accelerations were disregarded in the summary.

The short period and cyclic nature of the vertical acceleration trace were attributed to vibration of the vehicle frame and accelerometer mounting bracket.

Driver Appraisal

The driver subjectively evaluated each test run. Although accustomed to severe vehicle maneuvers, he attempted to evaluate the curb tests from an unbiased viewpoint. In his opinion, neither of the curbs produced vehicle response that would cause a "normal" (average) driver to lose steering control. Further, he believed that a driver in seat-belt restraint would suffer no injury.

The curb traversals were described as very minor "jolts" with slight side roll and minimum perceptible pitching motion. Undercarriage contact (usually on the oil pan), was described as "a sudden shock similar to hitting a deep pothole." The short-duration accelerations introduced by the suspension-bottoming were described as "barely noticeable and virtually insignificant."

Vehicle Attitude and Path

The test vehicle was partially or totally airborne in many of the tests, with at least one or more wheels losing ground contact. The driver mentioned several times in the last series of tests that the vehicle roll and pitch motion appeared to be less as the speeds and/or angles were increased. This may be attributed to degradation in the vehicle suspension (including shock absorbers) and steering system from repeated impacts. Although the front-end alignment was checked after each test, and corrected if necessary, there was noticeable degradation of the steering linkage. The frequency of realignment increased during the second series of tests, indicating a general looseness in the front end.

APPENDIX C

DISCUSSION OF FILM ANALYSIS AND THE COMPUTER PROGRAM

This appendix discusses the procedures for achieving film analyses of the full-scale vehicle-curb impact tests and translating them into a form suitable for comparison with and validation of HVOSM-predicted vehicle behavior characteristics. The data are those for vehicle impact with a Type E curb at 45 mph and 12.5-deg angle, designated Test N-6.

Included are a discussion of the coordinate axes system of film analysis, film data of an impact in a timed sequence, a discussion of correction factors, a sample analysis of film data, and the FORTRAN computer program listing for the ultimate translation of data from the film coordinate system to the HVOSM coordinate system.

Results of the tests on curbs Types C and E have been plotted by means of the Gerber Plotter for comparison with the HVOSM predictions (see Appendix D).

COORDINATE AXES SYSTEM FOR FILM ANALYSIS

Each test impact is recorded in a time sequence by two fixed cameras. During the impact sequence, the test vehicle's coordinate system of target points are related to the fixed axes of the two cameras, thus enabling a Vanguard Motion Analyzer to analyze the vehicle's behavior characteristics. Figure C-1 illustrates the vehicle's coordinate system of targets and the locations of the fixed cameras. The end-view camera parallel to the top edge of the curb measures horizontal distances (X coordinates) indicative of the vehicle's roll (*R*) and has as its fixed axis X3. The side-view camera perpendicular to the curb measures vertical distances (Y coordinates) indicative of the vehicle's pitch (*P*) and has as its fixed axis X9. (The numbers following the X and Y designations indicate the sequence in which the data were read from the analyzer and written into the computer program.) Figures C-2 and C-3, respectively, tabulate the roll and pitch data for Test N-6 as measured by the analyzer to the nearest 0.1 degree.

VEHICLE REFERENCE TARGETS

The 12-in.-diameter targets located on the rear and side of the vehicle and the rectangular target on the roof of the vehicle were used as references to determine the distances of the coordinates. The measured distances between the three reference targets and their assigned computer names (TARG1, TARG2, TARG3) are shown in Figures C-1 and C-4.

As an example of the use of the reference targets, the distance CGE(J), from the top of the curb to the roof target, can be determined at some instant by the proportionality relationship:

$$\frac{\mathrm{CGE(J)}}{(\mathrm{X5}-\mathrm{X3})}=\frac{\mathrm{REF2}}{(\mathrm{X2}-\mathrm{X1})}$$

$$\mathrm{CGE(J)}=\left(\frac{\mathrm{X5}-\mathrm{X3}}{\mathrm{X2}-\mathrm{X1}}\right)(\mathrm{TARG1})\ (\text{correction factors})$$

A minus value for CGE(J) would indicate that the roof target was to the left of X3 whereas a positive value would indicate that the roof target was to the right of X3.

FILM ANALYSIS CORRECTION FACTORS

The Vanguard Motion Analyzer can be used only to make measurements relative to a horizontal or a vertical line. Therefore, correction factors must be used to obtain the horizontal and vertical projections of skewed reference target line distances. To compensate for this situation, certain correction factors were made for each time increment reading. Correction factors included those for:

1. Vehicle roll.
2. Vehicle pitch.
3. Vehicle yaw.
4. The difference in the film speed of the parallel and perpendicular cameras.
5. Difference in camera distance between the location of the reference target and several vehicle coordinate points.
6. The vertical bumper height to satisfy the initial boundary conditions.

Fig. C-5 shows the correction factors necessary to compensate for the situations described in items (5) and (6).

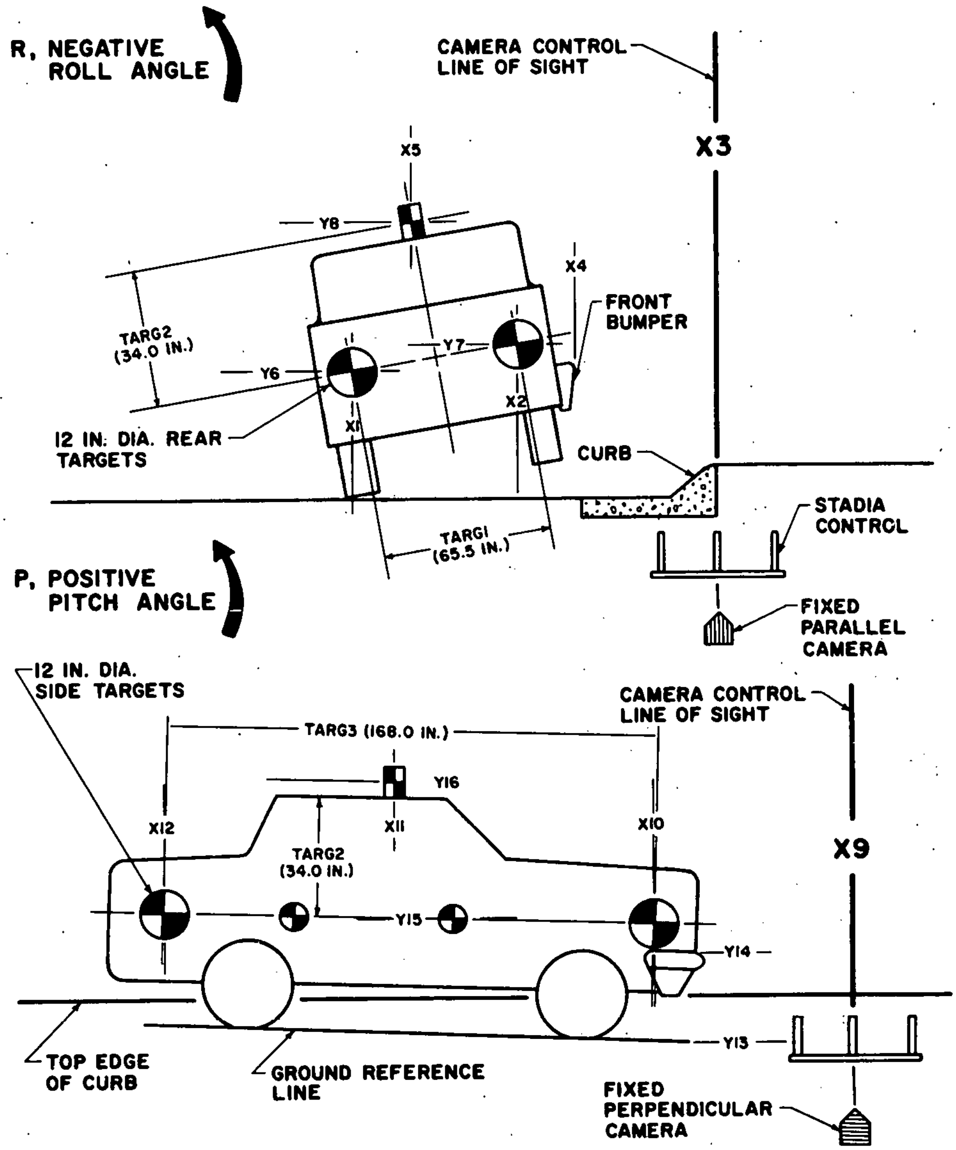


Figure C-1. Diagram of the test vehicle's coordinate axes system of target points with respect to the fixed cameras.

ROLL CORRECTION

The correction made for the vehicle roll angle and coordinate computer program identifications are shown in Figure C-4. Figure C-4 shows that the rear target vertical reference Vanguard reading (REF1) is dependent on the direction of roll. For example:

Positive Roll:
REF1 = E4 − 3

Negative Roll:
REF1 = E4 + E3

DISTANCE CORRECTION

The corrections made for the differences in camera distance between the locations of the reference targets and of several vehicle coordinate points are shown in Figure C-6. The identifications in Figure C-4 were those used in the computer program. Figure C-5 shows the magnitudes of the correction factors for the sample analysis of Test N-6, which is shown in Figure C-7.

BUMPER HEIGHT CORRECTION

The film from the side-view perpendicular camera was used to determine the bumper height relative to both the top edge of the curb and the level ground behind the curb. As shown in Figure C-8, the right front tire of the test vehicle was used as the ground reference line.

The ground reference line consists of a straight line established by two end points: (a) the instant in which the tire is on top of the curb, and (b) a time at which the

FILM DATA
FROM
CAMERA PARALLEL TO CURB

TEST NUMBER = N 6
FILM SPEED = 204.0 FPS
FRAME INTERVAL = 10.0

COORDINATES

R	X1	X2	X3	X4	X5	Y6	Y7	Y8
-0.4	939.0	2485.0	3940.0	3669.0	2411.0	4633.0	4650.0	5432.0
-0.6	1176.0	2703.0	3940.0	3851.0	2618.0	4652.0	4664.0	5443.0
-0.9	1430.0	2924.0	3940.0	4050.0	2835.0	4655.0	4674.0	5432.0
-0.9	1659.0	3133.0	3940.0	4206.0	3021.0	4672.0	4698.0	5444.0
-3.2	1885.0	3332.0	3940.0	4398.0	3187.0	4636.0	4721.0	5445.0
-4.8	2095.0	3519.0	3940.0	4555.0	3351.0	4610.0	4738.0	5444.0
-6.2	2288.0	3681.0	3940.0	4696.0	3505.0	4595.0	4749.0	5449.0
-7.0	2484.0	3861.0	3940.0	4863.0	3671.0	4621.0	4818.0	5464.0
-7.6	2631.0	3982.0	3940.0	4998.0	3804.0	4670.0	4852.0	5486.0
-7.2	2817.0	4151.0	3940.0	5142.0	3979.0	4703.0	4876.0	5486.0
-6.2	2993.0	4306.0	3940.0	5272.0	4149.0	4747.0	4890.0	5510.0
-4.2	3181.0	4478.0	3940.0	5426.0	4331.0	4772.0	4873.0	5509.0
-2.1	3344.0	4631.0	3940.0	5562.0	4500.0	4808.0	4859.0	5527.0
-0.2	3522.0	4786.0	3940.0	5695.0	4673.0	4814.0	4828.0	5521.0
0.7	3688.0	4930.0	3940.0	5818.0	4822.0	4843.0	4824.0	5517.0
0.6	3855.0	5089.0	3940.0	5956.0	4977.0	4879.0	4864.0	5548.0
0.2	4035.0	5246.0	3940.0	6093.0	5139.0	4881.0	4877.0	5527.0

Figure C-2. Tabulation of the test vehicle's roll (R) data for Test N-6.

FILM DATA
FROM
CAMERA PERPENDICULAR TO CURB

TEST NUMBER = N 6
FILM SPEED = 199.3 FPS
FRAME INTERVAL = 10.0

COORDINATES

X9	X10	X11	X12	Y13	Y14	Y15	Y16	P
3950.0	1505.0	923.0	-237.0	3294.0	3504.0	3591.0	3961.0	-0.0
3950.0	1931.0	1315.0	149.0	3303.0	3505.0	3602.0	3973.0	-0.2
3950.0	2384.0	1753.0	565.0	3300.0	3504.0	3592.0	3960.0	-0.3
3950.0	2833.0	2168.0	972.0	3307.0	3527.0	3597.0	3971.0	0.0
3950.0	3286.0	2589.0	1388.0	3312.0	3541.0	3616.0	3973.0	0.1
3950.0	3761.0	3051.0	1824.0	3308.0	3575.0	3634.0	3981.0	0.8
3950.0	4236.0	3496.0	2266.0	3313.0	3598.0	3658.0	4003.0	1.1
3950.0	4710.0	3942.0	2709.0	3317.0	3622.0	3667.0	4010.0	1.1
3950.0	5186.0	4399.0	3149.0	3319.0	3634.0	3674.0	4012.0	0.8
3950.0	5686.0	4886.0	3641.0	3325.0	3640.0	3679.0	4018.0	0.2
3950.0	6161.0	5328.0	4085.0	3330.0	3637.0	3679.0	4032.0	0.2
3950.0	6674.0	5822.0	4577.0	3334.0	3630.0	3664.0	4031.0	0.2
3950.0	7161.0	6284.0	5056.0	3336.0	3630.0	3647.0	4041.0	1.0
3950.0	7668.0	6769.0	5540.0	3339.0	3633.0	3635.0	4036.0	1.4
3950.0	8165.0	7244.0	6026.0	3351.0	3639.0	3635.0	4048.0	1.5
3950.0	8659.0	7724.0	6518.0	3348.0	3643.0	3653.0	4061.0	1.2
3950.0	9194.0	8221.0	7014.0	3350.0	3656.0	3656.0	4063.0	0.8

Figure C-3. Tabulation of the test vehicle's pitch (P) data for Test N-6.

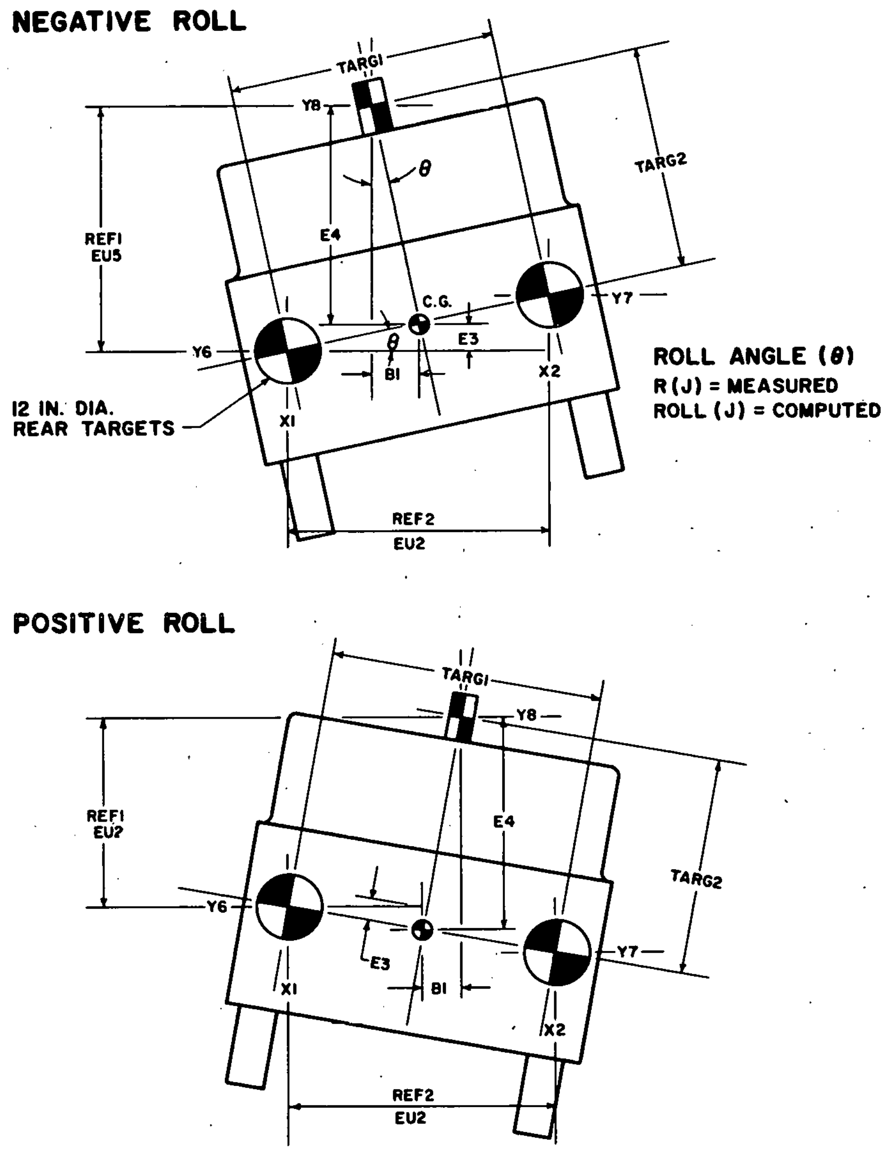


Figure C-4. Illustration of correction factors for vehicle roll.

vehicle came to a stable attitude. One of the lines on the moveable circular screen of the Vanguard Analyzer was used to "fix" the ground reference line between the two selected end points. It can be seen from the comparative HVOSM plots in Appendix D that the assumption of a straight ground reference line was reasonably valid.

The initial end point of the ground reference line could not be well defined and, hence, some error was introduced in the film data. A boundary condition was used to determine a correction factor. Assuming that the roll and pitch of the vehicle were negligible at the instant in which the tire was on top of the curb, the boundary condition requires that the calculated bumper height be corrected to conform with the measured bumper height less the height of the curb. The correction factor was then assumed to vary in a linear manner from its initial value to zero at the end point of the straight ground reference line.

The computer names used in determining the bumper height correction factors are shown in Figure C-8. Figure C-5 shows the magnitudes of the correction factors for the sample analysis of Test N-6 (Fig. C-7).

TRANSFORMATION FROM FILM TO HVOSM SYSTEM

The coordinate transformation from the film system to the HVOSM system is shown in Figure C-9. The identifications in Figure C-9 are those used in the computer program, which is shown as Figure C-10.

The lateral distance measurements of the vehicle bumper and center of gravity (C.G.) in the sample film analysis results (Fig. C-7) were in reference to the top edge of the curb designated YB3 in Figure C-9; the longitudinal measurements were in reference to a point on the curb designated XB3.

CORRECTIONS
FOR
LATERAL AND VERTICAL DISTANCE MEASUREMENTS
AND
BOUNDARY CONDITIONS

TYPE E-CURB
TEST NUMBER = N 6

TIME	DIST. FROM CAMERA PARALLEL TO CURB.			DIST FROM CAMERA NORMAL TO CURB.		DISTANCE CORRECTIONS			CORRECTION FOR BUMPER BOUNDARY CONDITION
	REAR TARGET	BUMPER	C.G.	BUMPER	C.G.	*CORR1* LAT DIST TO BUMPER	*CORR2* LAT DIST TO C.G.	*CORR3* VERT DIST TOP BUMPER	
(SEC)	(FT)	(FT)	(FT)	(FT)	(FT)				(UNITS)
-0.064	166.57	181.65	176.32	102.59	107.82	1.091	1.059	0.951	0.0
-0.014	170.07	185.35	179.84	101.38	106.45	1.090	1.057	0.952	0.0
0.037	173.62	189.02	183.45	100.21	105.15	1.089	1.057	0.953	0.0
0.087	177.03	192.59	186.87	99.31	104.05	1.088	1.056	0.954	-44.2
0.137	180.29	196.03	190.16	98.39	103.03	1.087	1.055	0.955	-40.5
0.187	183.87	199.51	193.70	97.70	102.09	1.085	1.053	0.957	-36.8
0.237	187.03	202.85	196.89	97.15	101.33	1.085	1.053	0.959	-33.2
0.287	190.13	206.08	200.00	96.63	100.62	1.084	1.052	0.960	-29.7
0.338	193.23	209.16	203.05	96.30	100.13	1.082	1.051	0.962	-26.4
0.388	196.40	212.57	206.31	96.02	99.62	1.082	1.050	0.964	-22.8
0.438	199.24	215.48	209.10	95.86	99.20	1.082	1.049	0.966	-19.7
0.488	202.36	218.60	212.17	95.74	98.88	1.080	1.048	0.968	-16.3
0.538	205.36	221.78	215.21	95.77	98.69	1.080	1.048	0.970	-12.9
0.588	208.34	224.87	218.23	95.84	98.52	1.079	1.047	0.973	-9.6
0.639	211.24	227.80	221.07	96.04	98.47	1.078	1.047	0.975	-6.4
0.689	214.29	230.99	224.14	96.38	98.49	1.078	1.046	0.979	-3.0
0.739	216.92	233.77	226.77	96.59	98.38	1.078	1.045	0.982	0.0

**** THE VALUES SHOWN IN THE ABOVE TABLE DO NOT INCLUDE PARALLAX CORRECTIONS MADE FOR VEHICLE ROLL ANGLE, PITCH ANGLE, AND YAW ANGLE ****

Figure C-5. Illustration of correction factors for certain distance measurements and boundary conditions for Test N-6 vehicle.

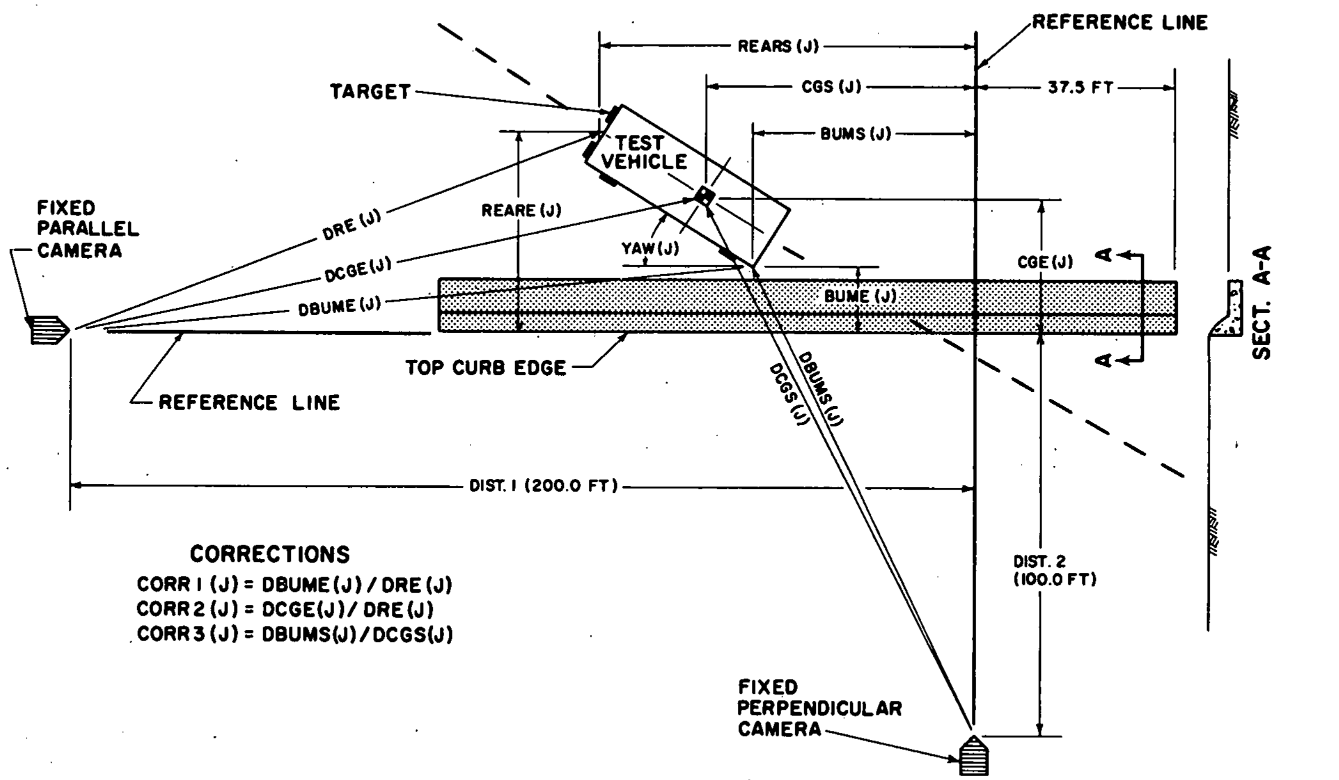


Figure C-6. Illustration of the translational measurements of correction factors for differences in distances between cameras and target references.

ANALYSIS
OF
FILM DATA
FROM
TEST ON TYPE E CURB

TEST NUMBER = N 6
VEHICLE SPEED = 45.3 MPH
VEHICLE ANGLE = 12.5 DEG

TIME	ROLL AZIMUTH	ANGLE COMPUTED	PITCH ANGLE	YAW ANGLE	BUMPER MID-HEIGHT VERT DIST	BUMPER MID-HEIGHT LAT DIST	BUMPER MID-HEIGHT LONG DIST	CENTER-OF-MASS VERT DIST	CENTER-OF-MASS LAT DIST	CENTER-OF-MASS LONG DIST	AVERAGE SPEED
(SEC)	(DEG)	(DEG)	(DEG)	(DEG)	(IN)	(FT)	(FT)	(IN)	(FT)	(FT)	(MPH)
-0.064	-0.4	-0.6	-0.0	11.4	10.8	-0.8	-3.4	27.3	-5.6	-9.7	49.0
-0.014	-0.6	-0.5	-0.2	11.4	10.8	-0.1	0.3	26.1	-4.9	-6.2	49.0
0.037	-0.9	-0.7	-0.3	11.1	10.8	0.6	3.9	25.7	-4.2	-2.6	50.2
0.087	-0.9	-1.0	0.0	10.8	10.8	1.2	7.5	21.5	-3.5	0.9	47.8
0.137	-3.2	-3.3	0.1	12.1	12.6	2.0	10.9	24.1	-2.8	4.2	45.9
0.187	-4.8	-4.9	0.8	11.2	17.0	2.7	14.4	27.2	-2.1	7.7	49.2
0.237	-6.2	-5.9	1.1	11.3	19.1	3.3	17.7	29.4	-1.5	10.9	44.5
0.287	-7.0	-7.7	1.1	12.7	21.5	4.1	21.0	30.4	-0.8	14.0	43.3
0.338	-7.6	-7.4	0.8	10.5	23.2	4.7	24.0	31.6	-0.2	17.1	42.2
0.388	-7.2	-7.3	0.2	12.1	23.5	5.4	27.4	31.8	0.5	20.3	45.3
0.438	-6.2	-6.1	0.2	13.5	22.1	6.0	30.3	30.5	1.2	23.1	38.9
0.488	-4.2	-4.4	0.2	12.5	20.5	6.7	33.4	28.1	1.8	26.2	42.8
0.539	-2.1	-2.7	1.0	12.0	18.6	7.4	36.6	24.0	2.5	29.2	42.5
0.588	-0.2	-0.6	1.4	13.4	19.0	8.2	39.7	23.6	3.2	32.2	42.0
0.639	0.7	0.8	1.5	13.0	18.1	8.8	42.6	22.3	3.9	35.1	39.6
0.689	0.6	0.7	1.2	13.5	19.3	9.6	45.7	24.6	4.6	38.1	42.8
0.739	0.2	0.2	0.8	17.8	20.6	10.4	48.5	25.1	5.4	40.7	37.3

**** THE VALUES SHOWN IN THE ABOVE TABLE HAVE BEEN TRANSFORMED TO CORRESPOND WITH THE HVOSM FIXED SPATIAL COORDINATE AXES SYSTEM ****

Figure C-7. Sample analysis of film data on vehicle behavior characteristics for Test N-6.

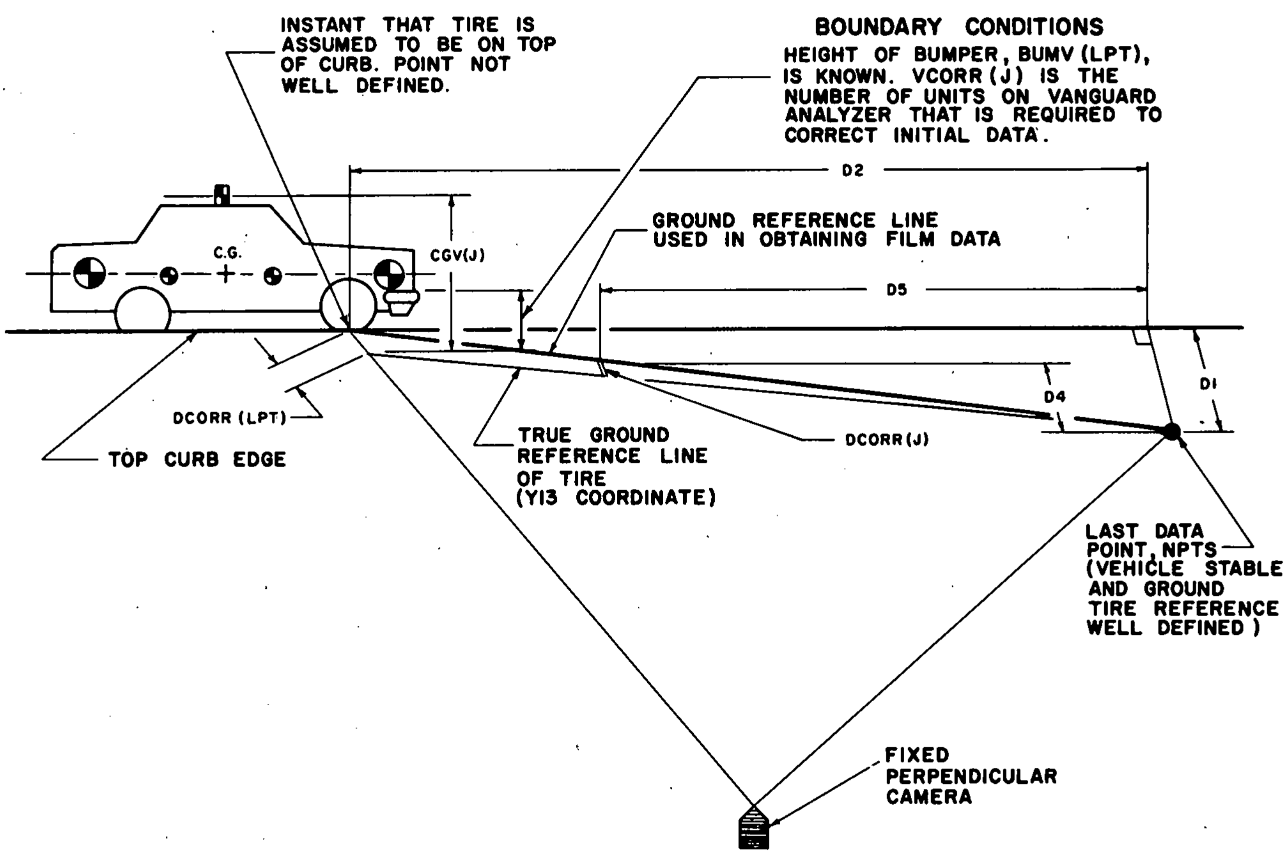


Figure C-8. Illustration of bumper height correction factors to satisfy boundary conditions at instant tire is on top of curb.

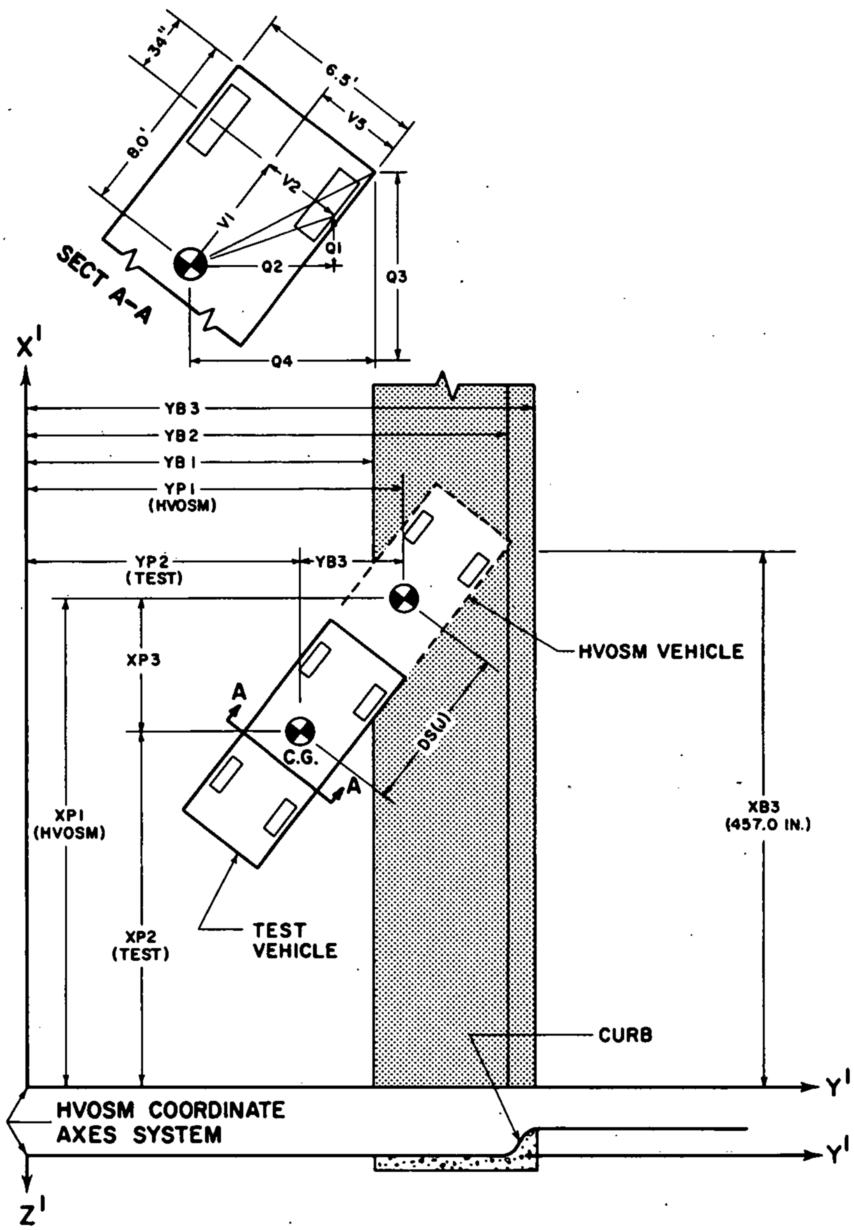


Figure C-9. Coordinate transformation from film system to HVOSM system.

```
//$WATFIV  JOB (655R5,7-G--,*30,002,EP),'  POST, ER  RF 845  '        '   JOB 114
      C
      C   ANALYSIS OF FILM DATA FOR CURB STUDY (RF 845)
      C
      C
1           DIMENSION BUME(50), BUMS(50), BUMV(50), CGE(50), CGS(50),
           * ROLL(50), YAW(50), DS(50), VEL1(50), CGV(50)
2           DIMENSION R(50), X1(50), X2(50), X3(50), X4(50), X5(50), Y6(50),
           * Y7(50), Y8(50), X9(50), X10(50), X11(50), X12(50), Y13(50),
           * Y14(50), Y15(50), Y16(50), P(50)
3           DIMENSION DBUMS(50), DCGS(50), CORR3(50), VCORR(50), DCORR(50)
4           DIMENSION REARE(50), REARS(50), DRE(50), DCGE(50), DBUME(50)
5           DIMENSION CORR1(50), CORR2(50)
      C
      C
      C   ***** INPUT DATA *****
      C
```

Figure C-10. FORTRAN computer program for analyzing film data of full-scale curb tests.

```
C   NTEST = TEST RUN NUMBER
C   NPTS = NUMBER OF DATA CARDS FOR PARALLEL CAMERA COORDINATE READINGS
C   SPEED = MEASURED SPEED OF VEHICLE (MPH)
C   ANGLE = VEHICLE ENCROACHMENT (YAW) ANGLE (DEG)
C   FILM1 = FILM SPEED OF PARALLEL CAMERA (FRAMES/SEC)
C   FILM2 = FILM SPEED OF PERPENDICULAR CAMERA (FRAMES/SEC)
C   FRAME1 = FRAME INTERVAL READING FOR PARALLEL CAMERA
C   FRAME2 = FRAME INTERVAL READING FOR PERPENDICULAR CAMERA
C   CAMHT = HEIGHT OF PERPENDICULAR CAMERA (IN)
C   DIST1 = DISTANCE FROM PARALLEL CAMERA TO THE PERPENDICULAR CAMERA
C           LINE OF SIGHT NORMAL TO CURB (FT)
C   DIST2 = DISTANCE FROM PERPENDICULAR CAMERA TO CURB (FT)
C   LPT = DATA READING NUMBER AT WHICH TIRE-CURB CONTACT OCCURS
C   XP1 = FIXED X-COORDINATE OF HVOSM C.G. (IN)
C   YP1 = FIXED Y-COORDINATE OF HVOSM C.G. (IN)
C   YB1 = LATERAL DISTANCE FROM HVOSM FIXED Y-AXIS TO FIRST CURB EDGE (IN)
C   YB3 = LATERAL DISTANCE FROM HVOSM FIXED Y-AXIS TO LAST CURB EDGE (IN)
C   XB3 = ZERO REFERENCE POINT RELATIVE TO FIXED X-AXIS OF HVOSM (IN)
C   CURBHT = HEIGHT OF CURB (IN)
C
C
          READ(5,100) NTEST, NPTS, SPEED, ANGLE, FILM1, FILM2,
         * FRAME1, FRAME2
      100 FORMAT( 2I5, 6F10.0)
C
          READ(5,400) XP1, YP1
      400 FORMAT( 2F10.0 )
C
          READ(5,401) YB1, YB3, XB3, CURBHT, LPT
      401 FORMAT( 4F10.0, I10 )
C
          READ(5,402) DIST1, DIST2, CAMHT
      402 FORMAT( 3F10.0 )
C
          WRITE(6,200) NTEST, FILM1, FRAME1
      200 FORMAT( ///, 1H1, 53X, 'FILM DATA', /, 56X,'FROM', /,
         * 47X,  'CAMERA PARALLEL TO CURB', //, 50X, 'TEST NUMBER = N',
         * I2, /, 51X, 'FILM SPEED = ', F5.1, 1X, 'FPS', /, 47X, 'FRAME INTE
         *RVAL = ', F4.1, ///)
          WRITE(6,201)
      201 FORMAT( 53X, 'COORDINATES', / )
          WRITE(6,202)
      202 FORMAT( 17X, 'R', 8X, 'X1', 8X, 'X2', 8X, 'X3', 8X, 'X4', 8X,

         * 'X5', 8X, 'Y6', 8X, 'Y7', 8X, 'Y8', //)
C
C  READ AND WRITE FILM DATA FROM PARALLEL CAMERA
C
          DO 10 J=1,NPTS
          READ(5,102) R(J), X1(J), X2(J), X3(J), X4(J), X5(J), Y6(J),
         * Y7(J), Y8(J)
      102 FORMAT( 9F8.0)
          WRITE(6,204)R(J), X1(J), X2(J), X3(J), X4(J), X5(J), Y6(J),
         * Y7(J), Y8(J)
      204 FORMAT( 10X, 9F10.1)
       10 CONTINUE
C
          WRITE(6,205) NTEST, FILM2, FRAME2
      205 FORMAT( ///, 1H1, 53X, 'FILM DATA', /, 56X, 'FROM', /, 45X,
         * 'CAMERA PERPENDICULAR TO CURB', //, 50X, 'TEST NUMBER = N',
         * I2, /, 51X, 'FILM SPEED = ', F5.1, 1X, 'FPS', /, 47X,
         * 'FRAME INTERVAL = ', F4.1, ///)
          WRITE(6,207)
      207 FORMAT( 53X, 'COORDINATES', / )
          WRITE(6,206)
      206 FORMAT( 17X, 'X9', 7X, 'X10', 7X, 'X11', 7X, 'X12', 7X, 'Y13',
         * 7X, 'Y14', 7X, 'Y15', 7X, 'Y16', 9X, 'P', //)
C
C  READ AND WRITE FILM DATA FROM PERPENDICULAR CAMERA
C
          DO 12 J=1,NPTS
          READ(5,102) X9(J), X10(J), X11(J), X12(J), Y13(J), Y14(J),
         * Y15(J), Y16(J), P(J)
```

Figure C-10. (Continued).

```
      WRITE(6,204)X9(J), X10(J), X11(J), X12(J), Y13(J), Y14(J),
     * Y15(J), Y16(J), P(J)
   12 CONTINUE
C
      WRITE(6,208) NTEST, SPEED, ANGLE
  208 FORMAT( ///, 1H1, 58X, 'ANALYSIS', /, 62X, 'OF', /, 58X,
     * 'FILM DATA', /, 61X, 'FROM', /, 53X, 'TEST ON TYPE E CURB', //,
     * 52X, 'TEST NUMBER = N', I2, /, 50X, 'VEHICLE SPEED = ', F4.1,
     * 1X, 'MPH', /, 50X, 'VEHICLE ANGLE = ', F4.1, 1X, 'DEG', ///)
C
      WRITE(6,210)
  210 FORMAT( 16X, 'TIME', 6X, 'ROLL ANGLE', 4X, 'PITCH', 4X, 'YAW',
     * 6X, 'BUMPER MID-HEIGHT', 9X, 'CENTER-OF-MASS', 5X, 'AVERAGE', /,
     * 23X, 'AZIMUTH', 1X, 'COMPUTED', 1X, 'ANGLE', 3X, 'ANGLE', 4X,
     * 'VERT', 4X, 'LAT', 5X, 'LONG', 4X, 'VERT', 4X, 'LAT', 5X,
     * 'LONG', 3X, 'SPEED', /, 57X, 'DIST', 4X, 'DIST', 4X, 'DIST', 4X,
     * 'DIST', 4X, 'DIST', 4X, 'DIST', /, 16X, '(SEC)', 3X, '(DEG)',
     * 3X, '(DEG)', 3X,'(DEG)', 3X, '(DEG)', 4X,'(IN)', 4X, '(FT)',
     * 4X, '(FT)', 4X, '(IN)', 4X, '(FT)', 4X, '(FT)', 3X, '(MPH)', / )
C
C  1963 CORNELL FORD DIMENSIONS
C
C    BUMHT = VERTICAL DISTANCE FROM GROUND TO TOP OF BUMPER (IN)
C    BUMWT = DEPTH OF BUMPER (IN)
C    BUMPT = VERTICAL DISTANCE FROM TOP OF BUMPER TO POINT ON BUMPER
C            WHERE BUMPER MOTION IS BEING INVESTIGATED (IN)
C    V1 = LONGITUDINAL DISTANCE FROM VEHICLE C.G. TO FRONT AXLE (IN)
C    V2 = LATERAL DISTANCE FROM LONGITUDINAL CENTERLINE OF VEHICLE
C         TO OUTSIDE OF TIRE (IN)
C    V4 = LONGITUDINAL DISTANCE FROM VEHICLE C.G. TO FRONT BUMPER FACE (IN)
C    V5 = LATERAL DISTANCE FROM LONGITUDINAL CENTERLINE OF VEHICLE
C         TO OUTSIDE OF TIRE (IN)
C    V6 = DISTANCE FROM VEHICLE C.G. TO REAR BUMPER
C    V8 = DISTANCE FROM FRONT SIDE 12-IN DIA. TARGET TO FRONT BUMPER (IN)
C
      BUMHT = 21.25
      BUMWT = 9.0
      BUMPT = 4.50
      V1 = 54.517
      V2 = 33.000
      V4 = 86.00
      V5 = 39.5
      V6 = 121.00
      V8 = 10.0
C
C  DISTANCE BETWEEN TARGETS ON VEHICLE (IN)
C
      TARG1 = 65.5
      TARG2 = 34.0
      TARG3 = 168.0
C
C  CONSTANTS
C
      ANGL = ANGLE
      SP = SPEED
      TD1 = FRAME1 / FILM1
      TD2 = FRAME2 / FILM2
      TDELTA = ABS( TD1 - TD2 )
      RAD = 3.1416 / 180.0
      G1 = 88.0 / 60.0
      G2 = G1 * 12.0
      DIST1 = DIST1 * 12.0
      DIST2 = DIST2 * 12.0
C
C
C
      DO 60 J=1,NPTS
C
C  FILM ANALYSIS OF DATA FROM PARALLEL CAMERA
C
      ROL = ABS( R(J) * RAD )
      E1 = TARG1 * COS(ROL)
      E2 = E1 * COS( ANGLE*RAD )
      E3 = (TARG1 / 2.0) * SIN(ROL)
      E4 = TARG2 * COS(ROL)
```

Figure C-10. (*Continued*).

```
      IF ( R(J) .LE. 0.0 ) GO TO 50
      REF1 = E4 - E3
      GO TO 52
   50 CONTINUE
      REF1 = E4 + E3
   52 CONTINUE
      REF1 = REF1 * COS( P(J)*RAD )
      EU1 = X4(J) - X3(J)
      EU2 = ABS( X2(J) - X1(J))
      EU3 = X5(J) - X3(J)
      EU4 = Y6(J) - Y7(J)
      EU5 = Y8(J) - Y6(J)
      REF2 = E2
      C1 = REF2 / EU2
      C2 = REF1 / EU5
      E5 = C2 * EU4
      ROLL(J) = ATAN( E5 / E1 )
      BUME(J) = C1 * EU1
      CGE(J) = C1 * EU3
      B1 = TARG2 * SIN(ROL)
      IF ( R(J) .GT. 0.0 ) GO TO 30
      CGE(J) = CGE(J) + B1
      GO TO 32
   30 CGE(J) = CGE(J) - B1
   32 CONTINUE
C
C
C  LATERAL DISTANCE CORRECTION (CGE) BASED ON DIFFERENT FILM SPEEDS OF
C  PARALLEL AND PERPENDICULAR CAMERAS
C
      IF ( TD2 .GT. TD1 ) GO TO 24
      CGE(J) = CGE(J) - SP*G2*TDELTA
      GO TO 26
   24 CONTINUE
      CGE(J) = CGE(J) + SP*G2*TDELTA
   26 CONTINUE
      SP = SP - ( SP / 100.0 )
C
C
C  FILM ANALYSIS OF DATA FROM PERPENDICULAR CAMERA
C
      REF3 = TARG3 * COS( ANGLE * RAD )
      REF3 = REF3 * COS( P(J)*RAD )
      REF4 = TARG2 * COS(ROL)
      REF4 = REF4 * COS( P(J)*RAD )
      SU1 = ABS( X10(J) - X12(J))
      SU2 = ABS( Y16(J) - Y15(J))
      SU3 = X10(J) - X9(J)
      SU4 = X11(J) - X9(J)
      SU5 = Y14(J) - Y13(J)
      SU6 = Y16(J) - Y13(J)
      C3 = REF4 / SU2
      C4 = REF3 / SU1
      BUMS(J) = C4 * SU3
      BUMS(J) = BUMS(J) + V8
      CGS(J) = C4 * SU4
      PITCH = ABS( P(J) * RAD )
      B2 = TARG2 * SIN(PITCH)
      IF ( P(J) .LT. 0.0 ) GO TO 34
      CGS(J) = CGS(J) + B2
      GO TO 36
   34 CGS(J) = CGS(J) - B2
   36 CONTINUE
      CGV(J) = C3 * SU6
      B3 = TARG2 * COS(ROL) * COS(PITCH)
      CGV(J) = CGV(J) - B3
C
C
C  PARALLAX CORRECTIONS TO COMPENSATE FOR LOCATION OF TARGET REFERENCE
C  RELATIVE TO VARIOUS DISTANCE MEASUREMENTS ( DOES NOT INCLUDE
C  CORRECTIONS MADE FOR ROLL, PITCH, AND YAW ANGLES )
C
C     CORR1 = LATERAL DISTANCE TO BUMPER
C     CORR2 = LATERAL DISTANCE TO C.G.
```

Figure C-10. (Continued).

```
C     CORR3 = BUMPER HEIGHT
C
          R1 = DIST2 - BUME(J)
          R2 = DIST2 - CGE(J)
          R3 = BUMS(J)
          R4 = CGS(J)
          DBUMS(J) = SQRT( R1**2 + R3**2 )
          DCGS(J) = SQRT( R2**2 + R4**2 )
          CORR3(J) = DBUMS(J) / DCGS(J)
C
          REARS(J) = CGS(J) - V6*COS( ANGLE*RAD )
          REARE(J) = CGE(J) - V6*SIN( ANGLE*RAD )
          R1 = DIST1 + BUMS(J)
          R2 = DIST1 + CGS(J)
          R3 = DIST1 + REARS(J)
          R4 = BUME(J)
          R5 = CGE(J)
          R6 = REARE(J)
          DRE(J) = SQRT( R3**2 + R6**2 )
          DCGE(J) = SQRT( R2**2 + R5**2 )
          DBUME(J) = SQRT( R1**2 + R4**2 )
          CORR1(J) = DBUME(J) / DRE(J)
          CORR2(J) = DCGE(J) / DRE(J)
C
          BUME(J) = BUME(J) * CORR1(J)
          CGE(J) = CGE(J) * CORR2(J)
          C3 = C3 * CORR3(J)
          IF ( J .GT. 1 ) GO TO 54
          GO TO 60
      54 CONTINUE
C
C
C     YAW ANGLE
C
          E10 = CGE(J) - CGE(J-1)
          S10 = CGS(J) - CGS(J-1)
          ANG = ATAN( E10 / S10 )
          YAW(J) = ANG / RAD
          ANGLE = ANG / RAD
C
      60 CONTINUE
C
C
C
C     BUMPER HEIGHT CORRECTION TO SATISFY BOUNDARY CONDITIONS AT
C     INSTANT TIRE IS ON TOP OF CURB
C
          DO 90 J=1,NPTS
          ROL = ABS( R(J) * RAD )
          REF4 = TARG2 * COS(ROL)
          REF4 = REF4 * COS( P(J)*RAD )
          SU2 = ABS( Y16(J) - Y15(J))
          SU5 = Y14(J) - Y13(J)
          C3 = REF4 / SU2
          C3 = C3 * CORR3(J)
          IF ( J .GE. LPT ) GO TO 81
          VCORR(J) = 0.0
          B1 = BUMHT - CURBHT
          BUMV(J) = B1 - BUMPT
          GO TO 84
      81 IF ( J .GT. LPT ) GO TO 83
          VCORR(LPT) = ( B1 / C3 ) - SU5
          DCORR(LPT) = VCORR(LPT) * ( DBUMS(LPT) / CAMHT )
          D1 = BUME(NPTS) - BUME(LPT)
          D2 = BUMS(NPTS) - BUMS(LPT)
          D3 = SQRT( D1**2 + D2**2 )
          BUMV(LPT) = C3 * ( SU5 + VCORR(LPT))
          BUMV(LPT) = BUMV(LPT) - BUMPT
      83 CONTINUE
          D4 = BUME(NPTS) - BUME(J)
          D5 = BUMS(NPTS) - BUMS(J)
          D6 = SORT( D4**2 + D5**2 )
          DCORR(J) = DCORR(LPT) * ( D6/D3 )
```

Figure C-10. (Continued).

```
         VCORR(J) = DCORR(J) * ( CAMHT / DBUMS(LPT))
         BUMV(J) = C3 * ( SU5 + VCORR(J))
         BUMV(J) = BUMV(J) - BUMPT
      84 CONTINUE
C
C     AVERAGE HEADING SPEED
C
         IF( J .GT. 1 ) GO TO 91
         GO TO 90
      91 CONTINUE
         CGVERT = C3 * VCORR(J)
         CGV(J) = ( CGV(J) + CGVERT ) * CORR3(J)
         E10 = CGE(J) - CGE(J-1)
         S10 = CGS(J) - CGS(J-1)
         V10 = CGV(J) - CGV(J-1)
         DS(J) = SQRT( E10**2 + S10**2 + V10**2 )
         VEL1(J) = ( DS(J)) / ( TD2*G2 )
      90 CONTINUE
C
C
C     TRANSFORMATION FROM FILM COORDINATE SYSTEM TO HVOSM COORDINATE SYSTEM
C
         V3 = SQRT( V1**2 + V2**2 )
         A1 = ATAN( V2 / V1 )
         A1 = A1 / RAD
         A2 = 90.0 - ANGL - A1
         A2 = A2 * RAD
         Q2 = V3 * COS( A2 )
         Q1 = V3 * SIN( A2 )
         YP2 = YB1 - Q2
         YP3 = YP1 - YP2
         XP3 = YP3 / TAN( ANGL * RAD )
         XP2 = XP1 - XP3
         D1 = SQRT( YP3**2 + XP3**2 )
         VEL = SPEED * G2
         T1 = D1 / VEL
         V6 = SQRT( V4**2 + V5**2 )
         A3 = ATAN( V5 / V4 )
         A3 = A3 / RAD
         A4 = 90.0 - ANGL - A3
         A4 = A4 * RAD
         Q3 = V6 * SIN( A4 )
         Q4 = V6 * COS( A4 )
         IF ( YP1 .GT. YP2 ) GO TO 15
         TIME = T1
         GO TO 16
      15 TIME = -T1
      16 CONTINUE
         TIM = TIME
         BUMEY = BUME(1) / 12.0
         BUMEX = BUMS(1) / 12.0
         CGEE = CGE(1) / 12.0
         CGSS = CGS(1) / 12.0
         VEL1(1) = VEL1(2)
         YAW(1) = YAW(2)
C
C
C     WRITE TEST RESULTS IN HVOSM FIXED SPATIAL COORDINATE AXES SYSTEM
C
         DO 70 J=1,NPTS
C
         BUME(J) = BUME(J) / 12.0
         BUME(J) = BUME(J) - BUMEY
         BUME(J) = BUME(J) + ( YP2 + Q4 ) / 12.0
         BUME(J) = BUME(J) - YB3 / 12.0
         BUMS(J) = BUMS(J) / 12.0
         BUMS(J) = BUMS(J) - BUMEX
         BUMS(J) = BUMS(J) + ( XP2 + Q3 ) / 12.0
         BUMS(J) = BUMS(J) - XB3 / 12.0
         CGE(J) = CGE(J) / 12.0
         CGE(J) = CGE(J) - CGEE
         CGE(J) = CGE(J) + ( YP2 / 12.0 )
         CGE(J) = CGE(J) - YB3 / 12.0
         CGS(J) = CGS(J) / 12.0
```

Figure C-10. **(Continued).**

```
          CGS(J) = CGS(J) - CGSS
          CGS(J) = CGS(J) + ( XP2 / 12.0 )
          CGS(J) = CGS(J) - XB3 / 12.0
          ROLL(J) = ROLL(J) / RAD
          WRITE(6,300) TIM , R(J), ROLL(J), P(J), YAW(J), BUMV(J), BUME(J),
         * BUMS(J), CGV(J), CGE(J), CGS(J), VEL1(J)
      300 FORMAT( 15X, F6.3, 11F8.1 )
          WRITE(7,301) ROLL(J), P(J), BUMV(J), BUME(J), BUMS(J), VEL1(J)
      301 FORMAT ( 6F10.4 )
          TIM = TIM + TD2
       70 CONTINUE
C
          WRITE(6,302)
      302 FORMAT( //, 21X, '**** THE VALUES SHOWN IN THE ABOVE TABLE HAVE BE
         *EN TRANSFORMED TO CORRESPOND WITH THE', /,
         * 26X, 'HVOSM FIXED SPATIAL COORDINATE AXES SYSTEM ****' )
C
C
C
C  WRITE CORRECTIONS FOR DISTANCE MEASUREMENTS AND BOUNDARY CONDITIONS
C
          WRITE(6,321) NTEST
      321 FORMAT( 1H1, //, 60X, 'CORRECTIONS', /, 64X, 'FOR', /, 45X,
         * 'LATERAL AND VERTICAL DISTANCE MEASUREMENTS', /, 64X, 'AND',
         * /, 54X, 'BOUNDARY CONDITIONS',//,60X, 'TYPE E-CURB', /,
         * 57X, 'TEST NUMBER = N', I2, // )
C
          WRITE(6,322)
      322 FORMAT( 77X, 'DISTANCE CORRECTIONS', 7X, 'CORRECTION',/,
         * 16X, 'TIME', 10X, 'DIST FROM CAMERA', 9X, 'DIST FROM CAMERA',
         * 2X, '*CORR1*', 3X, '*CORR2*', 4X, '*CORR3*', 6X, 'FOR', /,
         * 30X, 'PARALLEL TO CURB', 10X, 'NORMAL TO CURB', 3X, 'LAT DIST',
         * 2X, 'LAT DIST', 2X, 'VERT DIST', 4X, 'BUMPER', /, 73X,
         * 'TO BUMPER', 2X, 'TO C.G.', 2X, 'TOP BUMPER', 2X, 'BOUNDARY',
         * /, 22X, 'REAR TARGET', 2X, 'BUMPER', 5X, 'C.G.', 5X, 'BUMPER',
         * 5X, 'C.G.', 34X, 'CONDITION', /, 16X, '(SEC)', 5X, '(FT)', 6X,
         * '(FT)', 6X, '(FT)', 6X, '(FT)', 6X, '(FT)',35X, '(UNITS)', / )
C
          TIM = TIME
          DO 325 J=1,NPTS
          R1 = DRE(J) / 12.0
          R2 = DBUME(J) / 12.0
          R3 = DCGE(J) / 12.0
          R4 = DBUMS(J) / 12.0
          R5 = DCGS(J) / 12.0
          WRITE(6,323) TIM, R1, R2, R3, R4, R5, CORR1(J), CORR2(J),
         * CORR3(J), VCORR(J)
      323 FORMAT( 15X, F6.3, 5F10.2, 3F10.3, F10.1 )
          TIM = TIM + TD2
      325 CONTINUE
          WRITE(6,327)
      327 FORMAT( //,21X, '**** THE VALUES SHOWN IN THE ABOVE TABLE DO NOT I
         *NCLUDE PARALLAX CORRECTIONS MADE FOR ', /,
         * 26X, 'VEHICLE ROLL ANGLE, PITCH ANGLE, AND YAW ANGLE ****' )
C
C
C
          WRITE(6,303)
      303 FORMAT( 1H1 )
C
C
          STOP
          END

//$DATA
```

Figure C-10. (Continued).

APPENDIX D

VALIDATION AND CORRELATION DATA—COMPARISON OF HVOSM PREDICTIONS AND FILM ANALYSES

Figures D-1 through D-18 show the behavior characteristics for the full-scale-test vehicle and the HVOSM vehicle by a Gerber plot of the full-scale test results for curbs Types C and E for comparison with the HVOSM predictions for these curbs.

Each figure is comprised of two parts. Part (a) plots vehicle pitch angle, roll angle, and bumper rise with respect to lateral distance behind the curb. Part (b) shows vehicle path and speed with respect to distance along the curb from the point of impact.

Figures D-19 and D-20 are photographic comparisons at corresponding time intervals of full-scale-test vehicle behavior characteristics and HVOSM predictions of vehicle behavior for Tests N-7 and N-18, respectively.

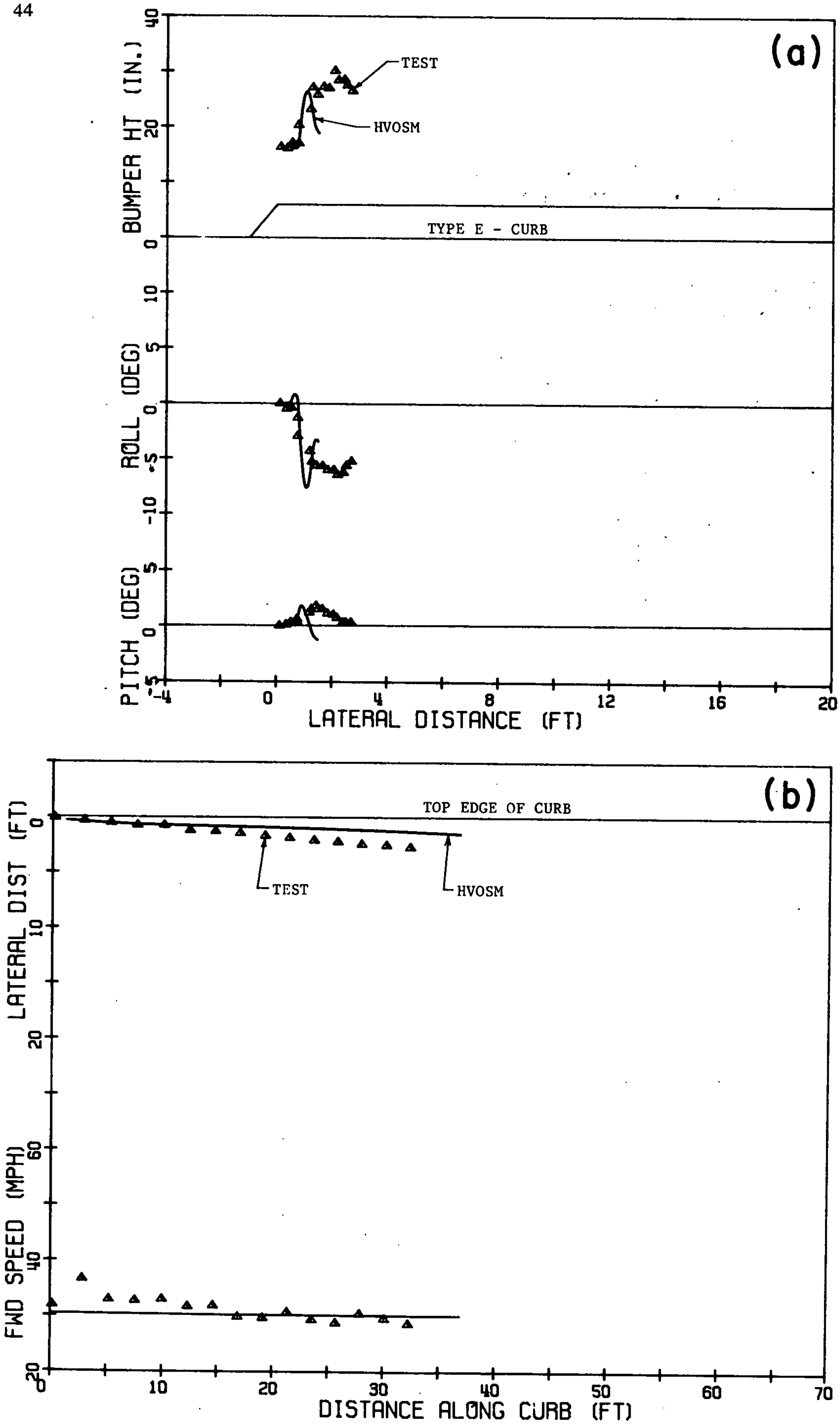


Figure D-1. Curb Type E, Test N-2 at 30-mph and 5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

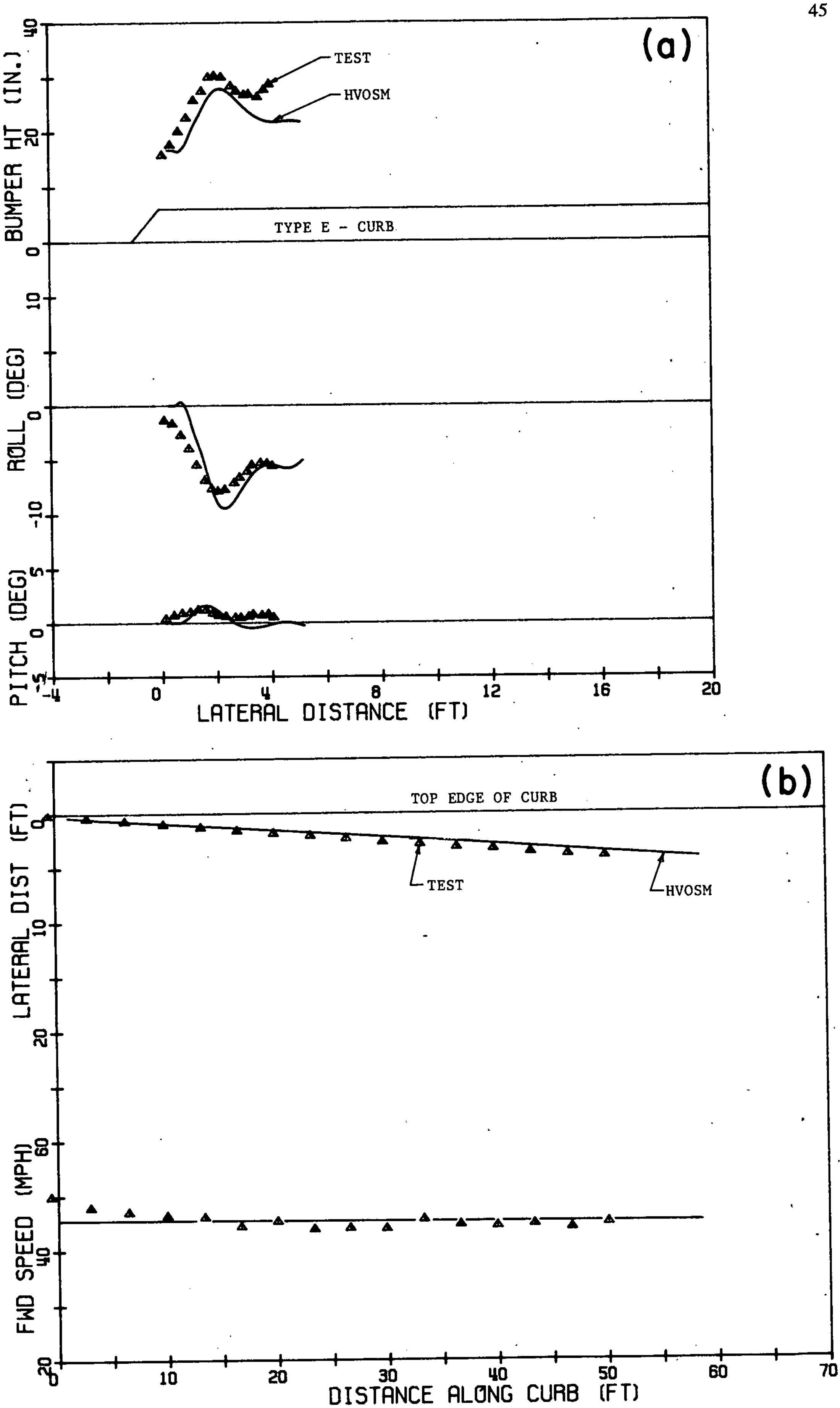


Figure D-2. Curb Type E, Test N-3 at 45-mph and 5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

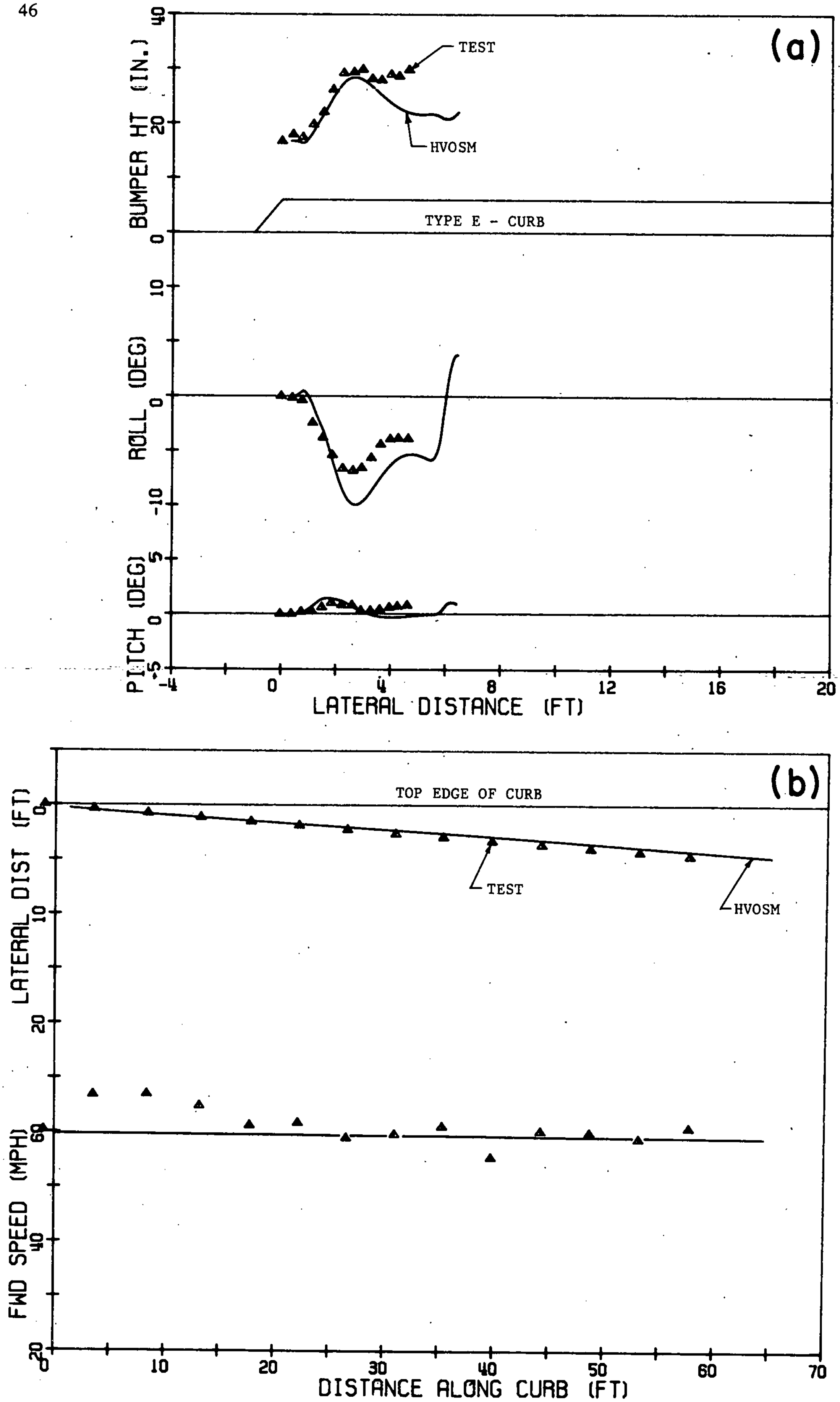


Figure D-3. Curb Type E, Test N-4 at 60-mph and 5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

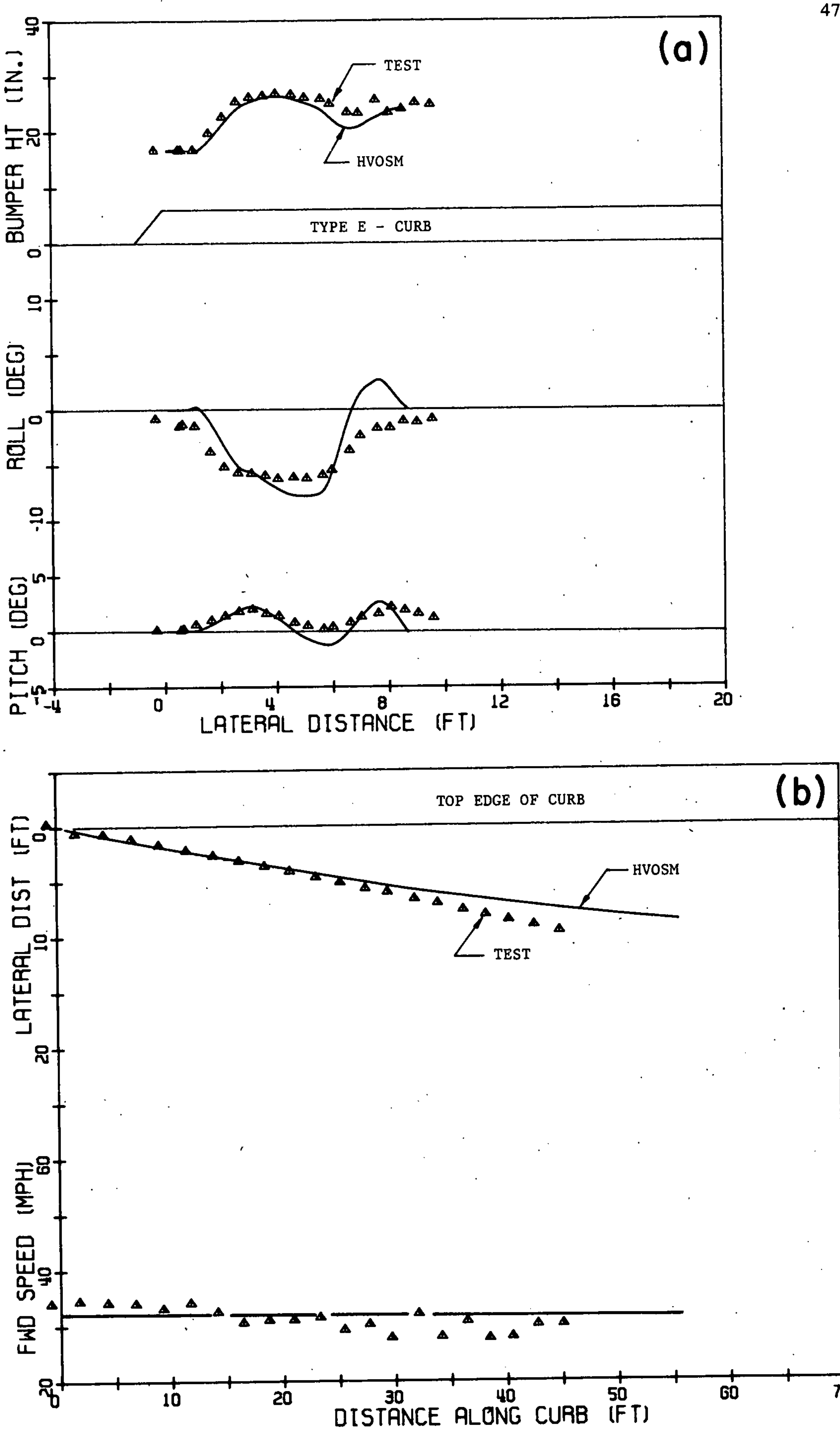


Figure D-4. Curb Type E, Test N-5 at 30-mph and 12.5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

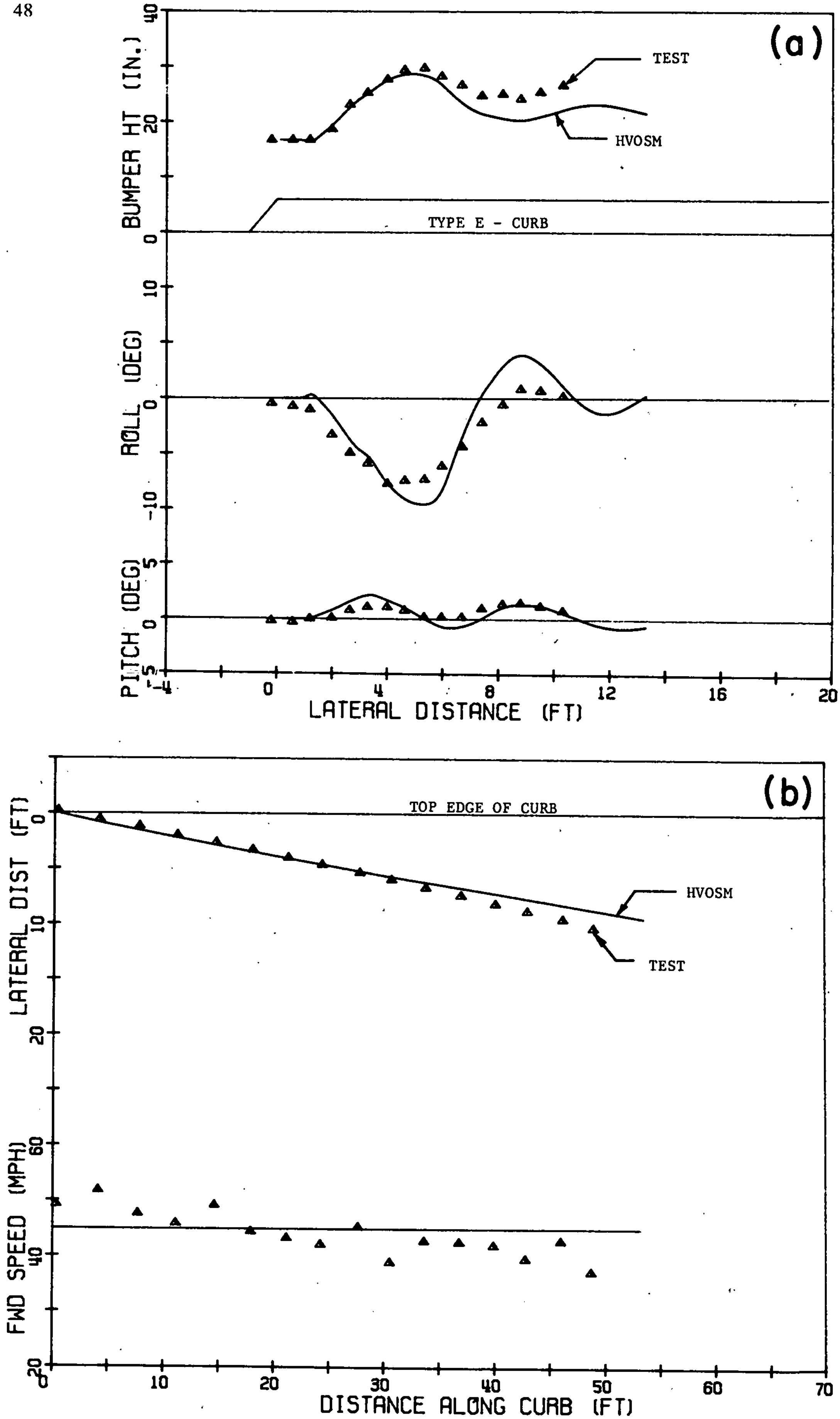


Figure D-5. Curb Type E, Test N-6 at 45-mph and 12.5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

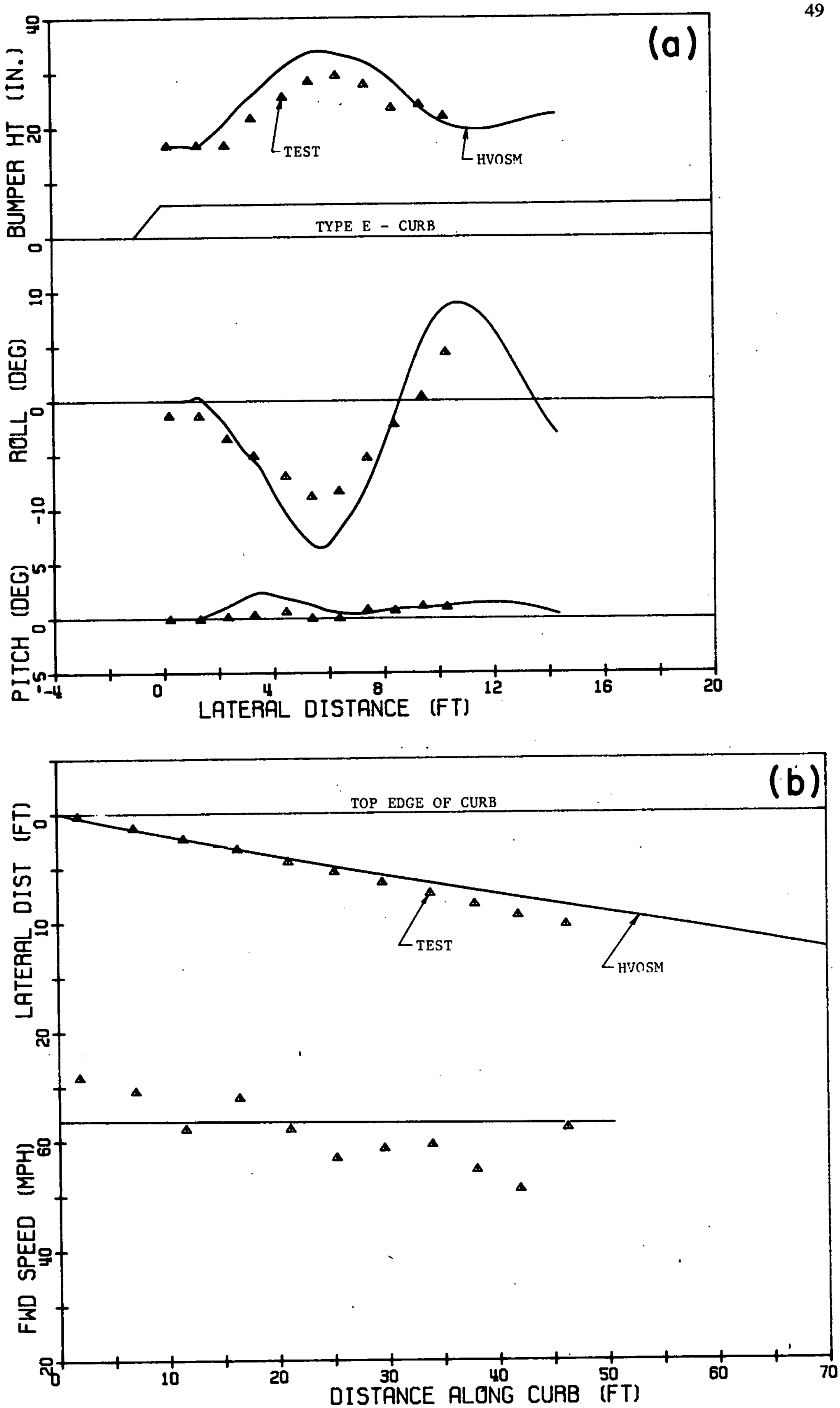


Figure D-6. Curb Type E, Test N-7 at 60-mph and 12.5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

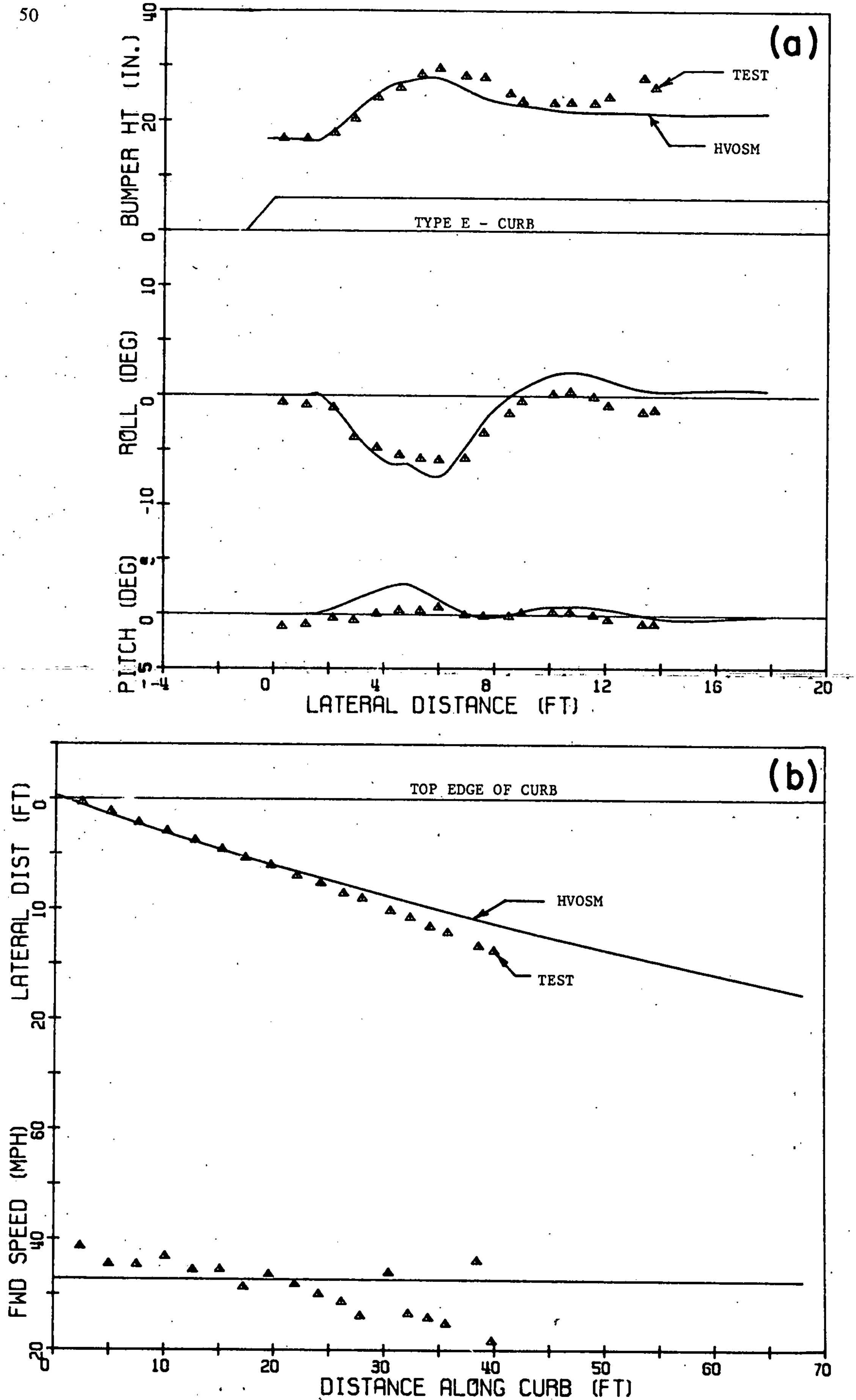


Figure D-7. Curb Type E, Test N-8 at 30-mph and 20-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

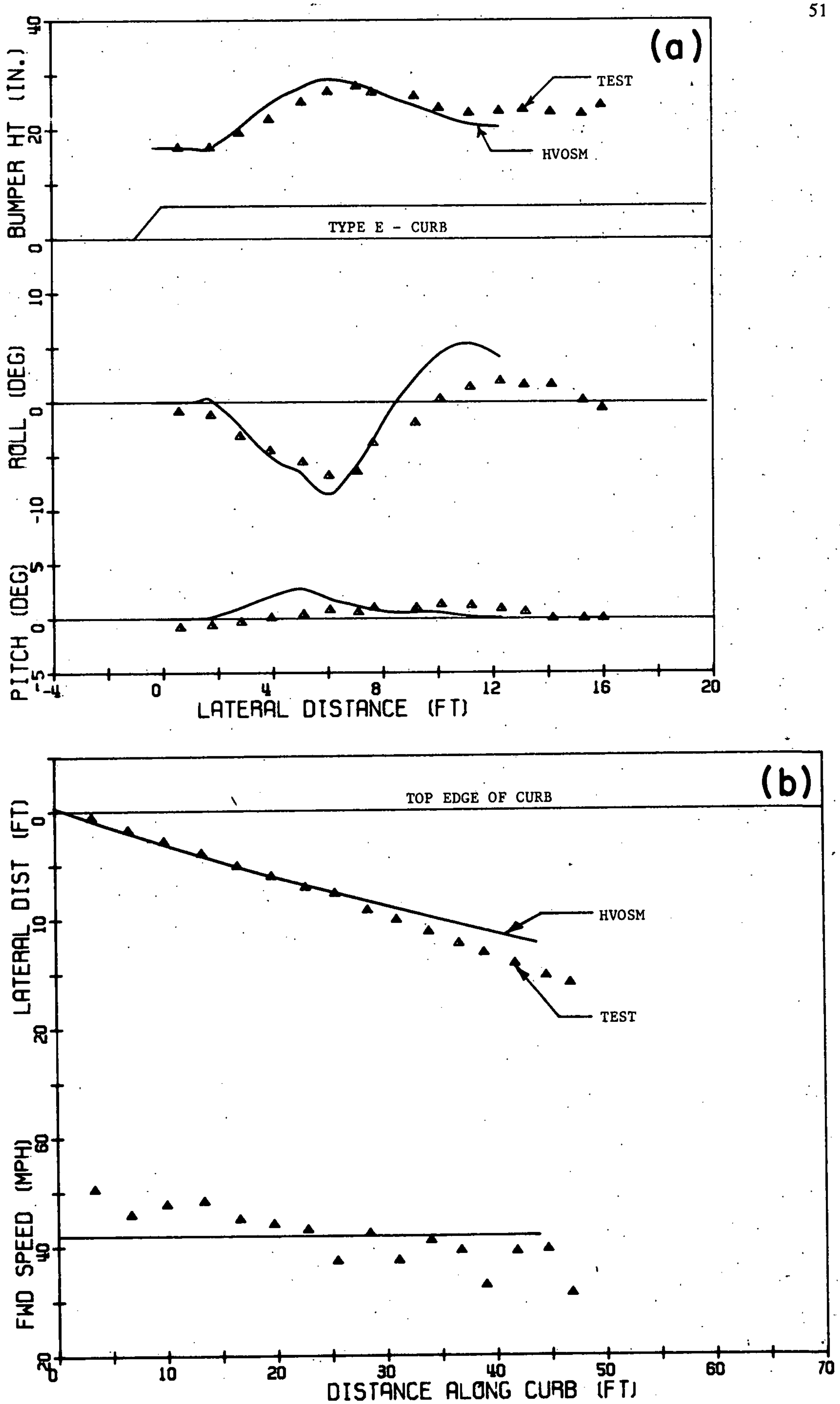
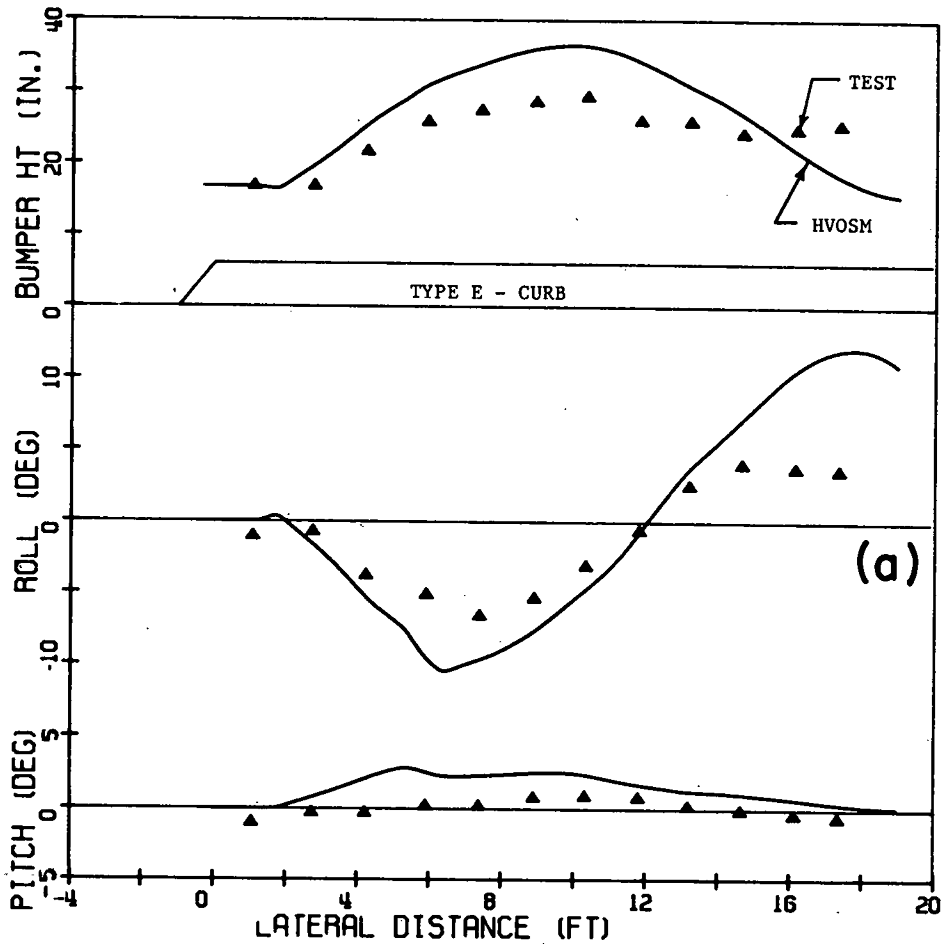


Figure D-8. Curb Type E, Test N-9 at 45-mph and 20-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.



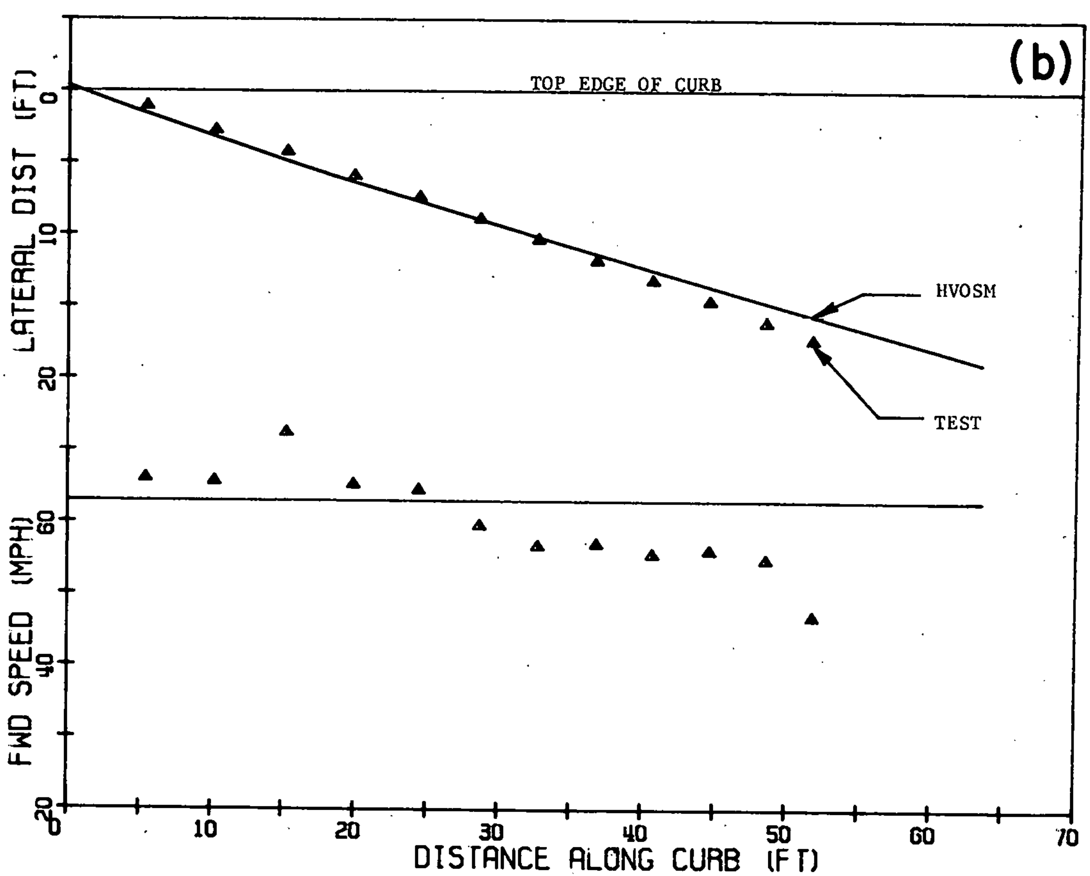


Figure D-9. Curb Type E, Test N-10 at 60-mph and 20-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

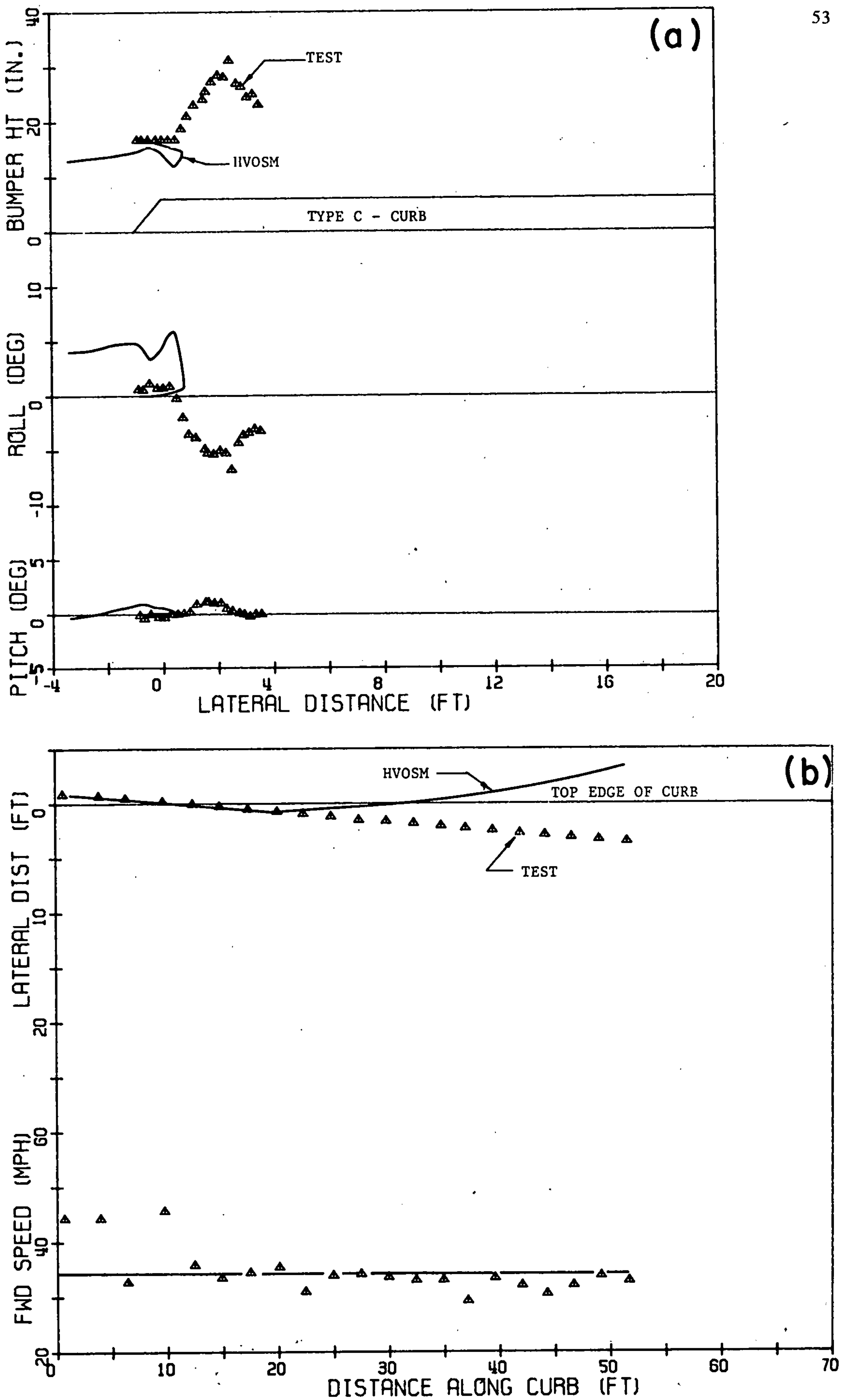


Figure D-10. Curb Type C, Test N-11 at 30-mph and 5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

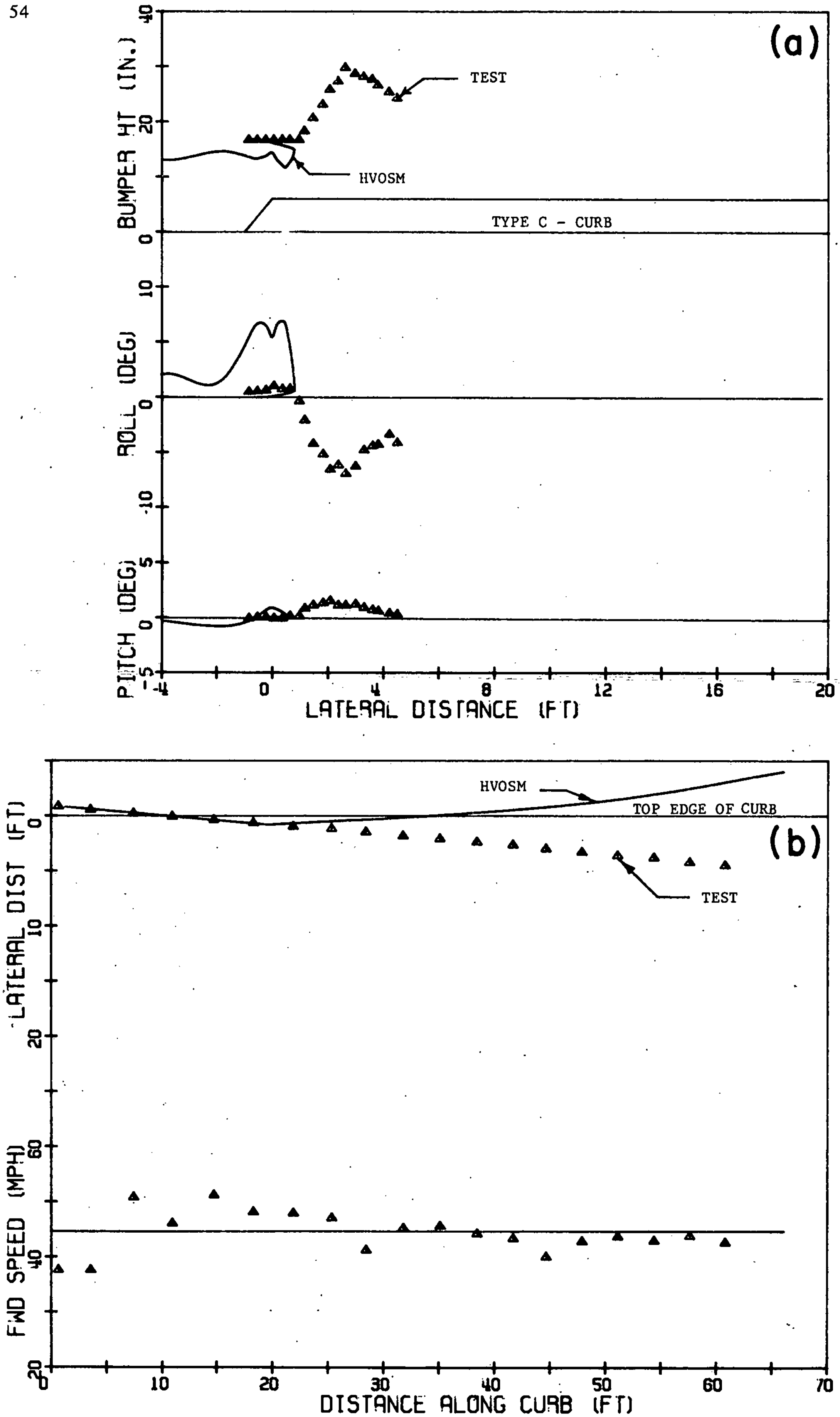


Figure D-11. Curb Type C, Test N-12 at 45-mph and 5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

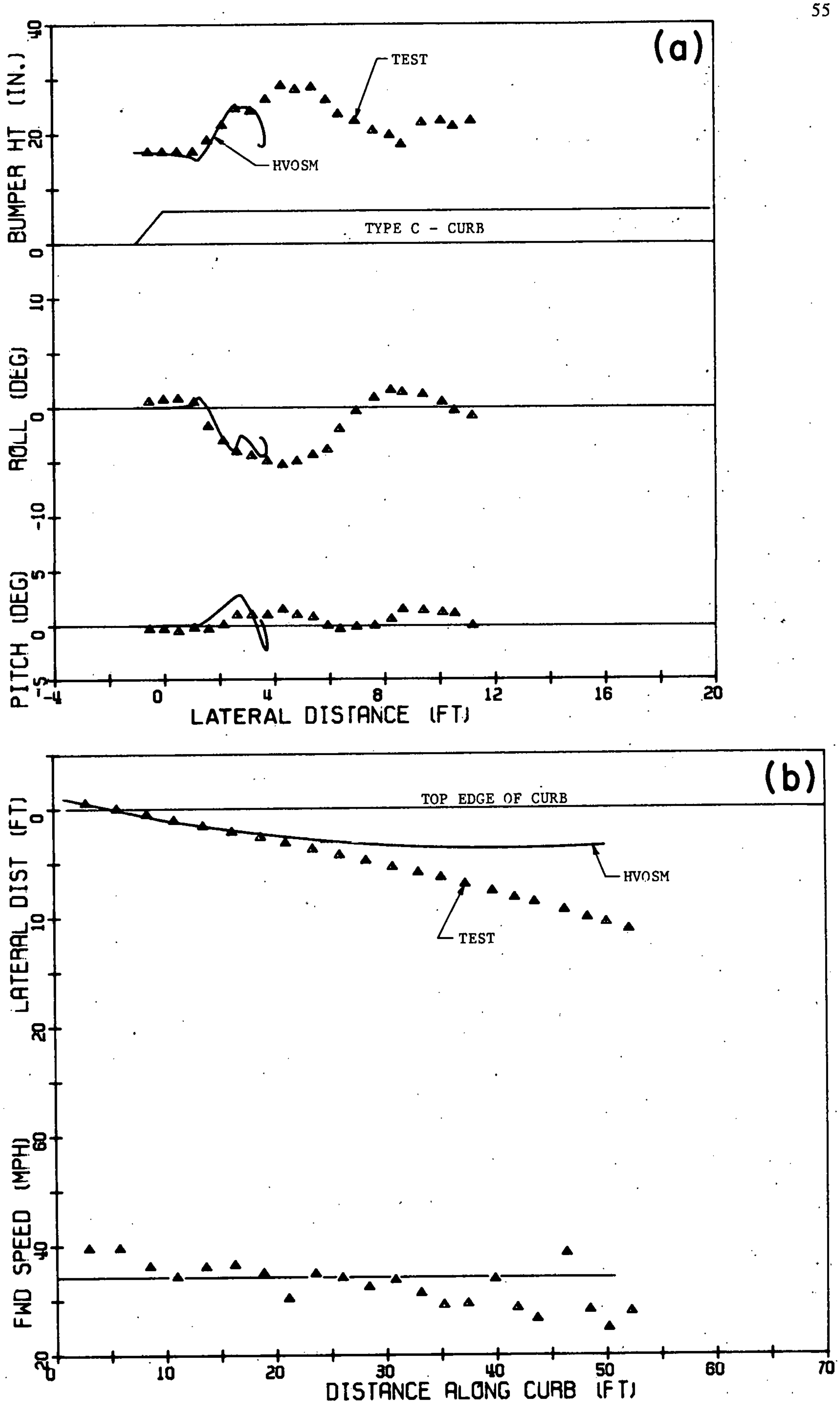
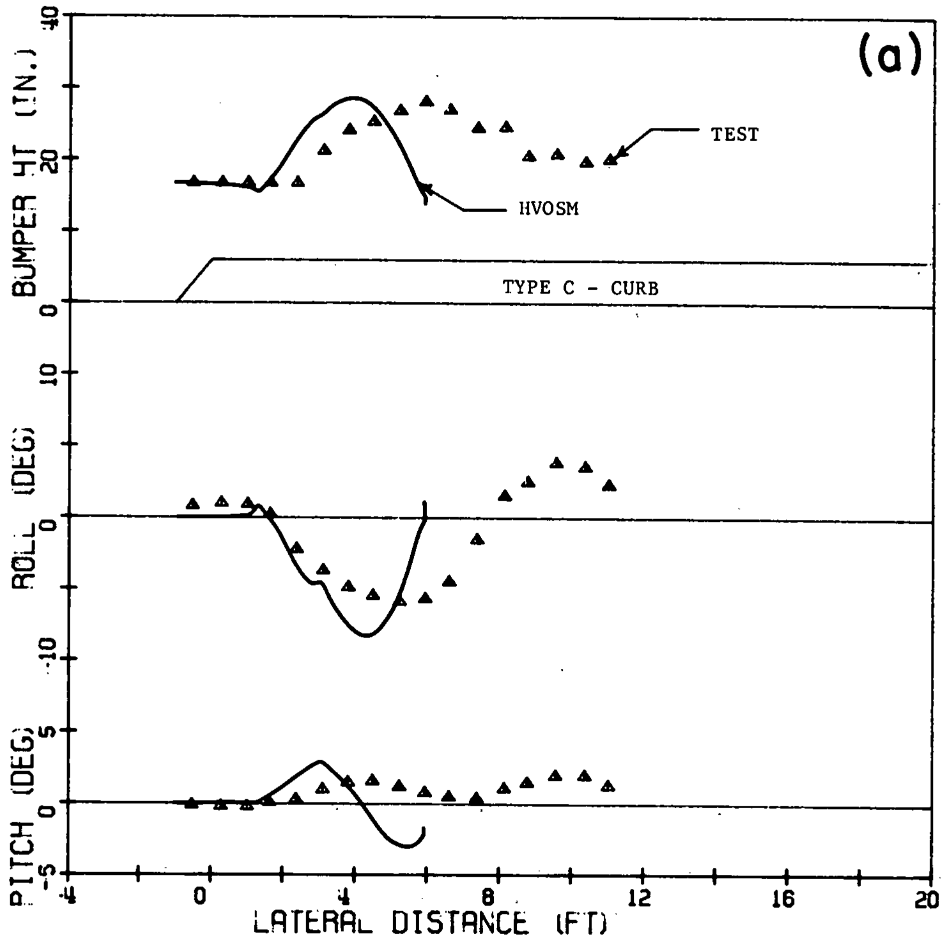


Figure D-12. Curb Type C, Test N-13 at 30-mph and 12.5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.



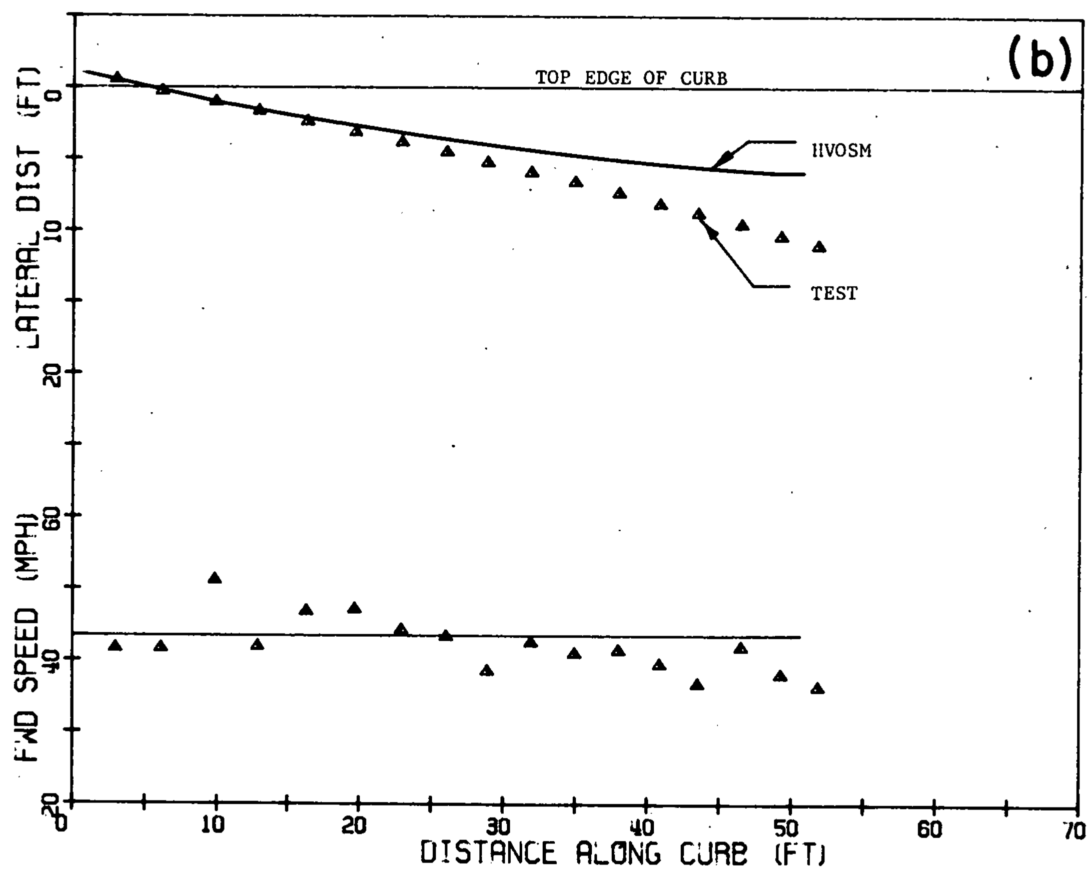


Figure D-13. Curb Type C, Test N-14 at 45-mph and 12.5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

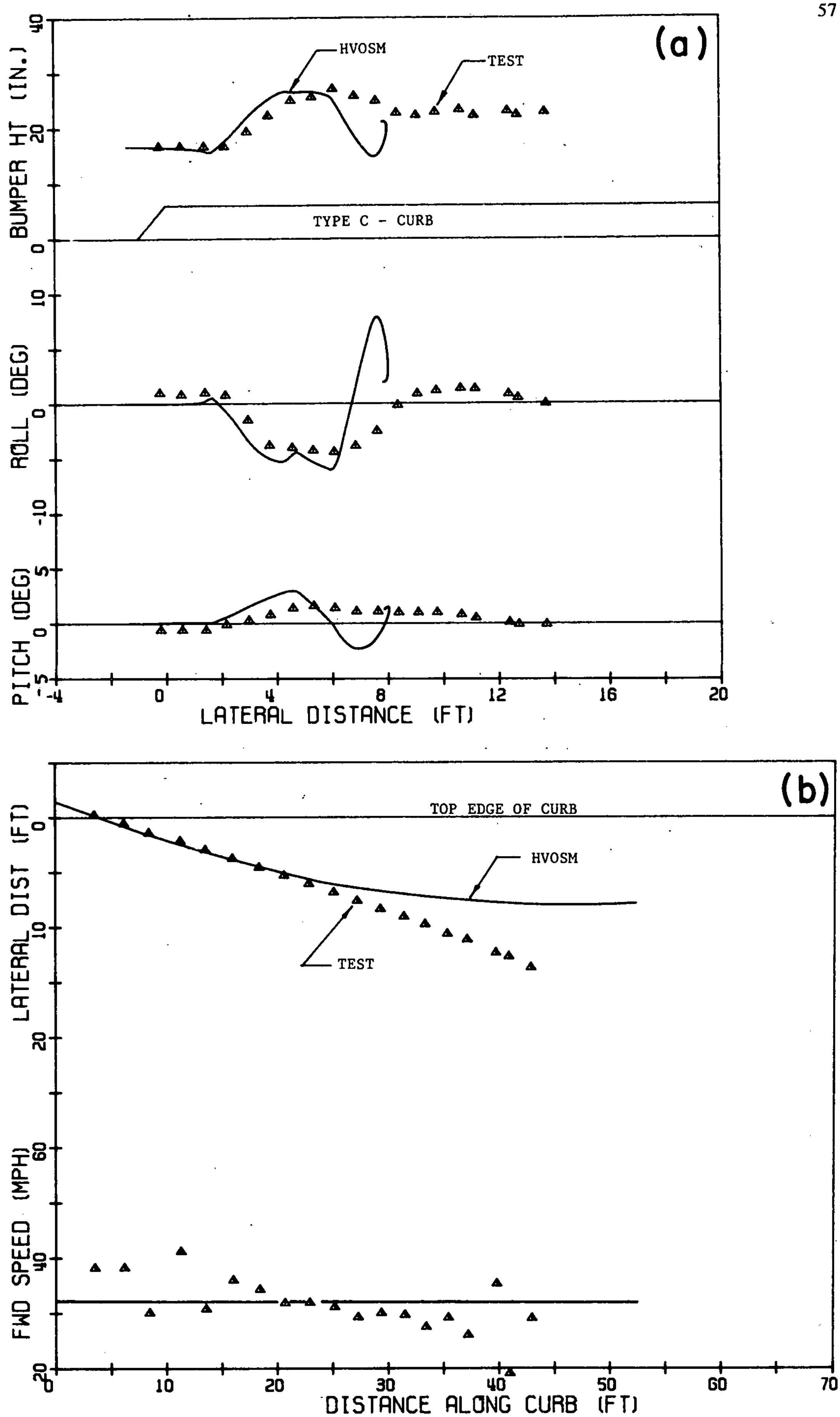


Figure D-14. Curb Type C, Test N-15 at 30-mph and 20-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

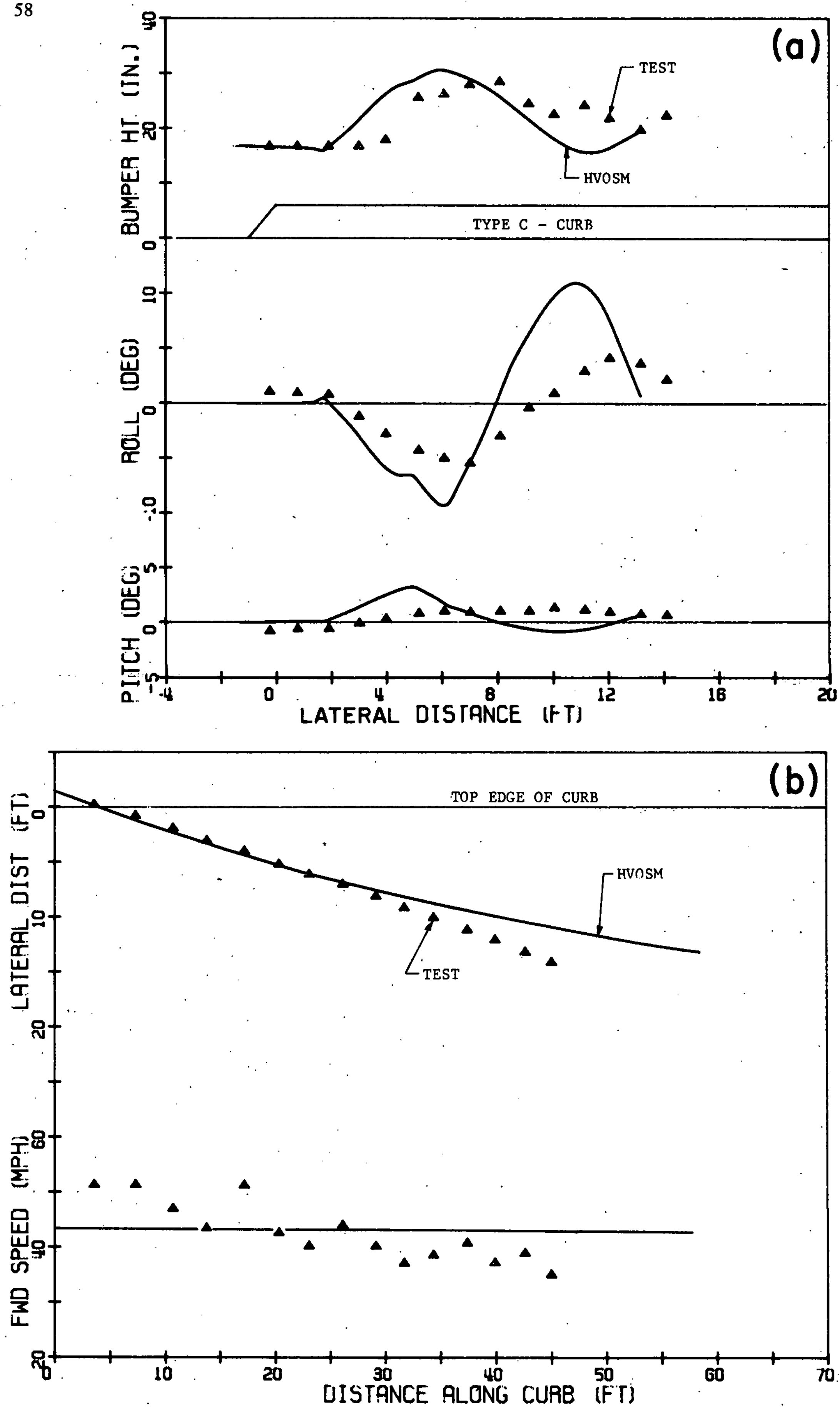


Figure D-15. Curb Type C, Test N-16 at 45-mph and 20-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

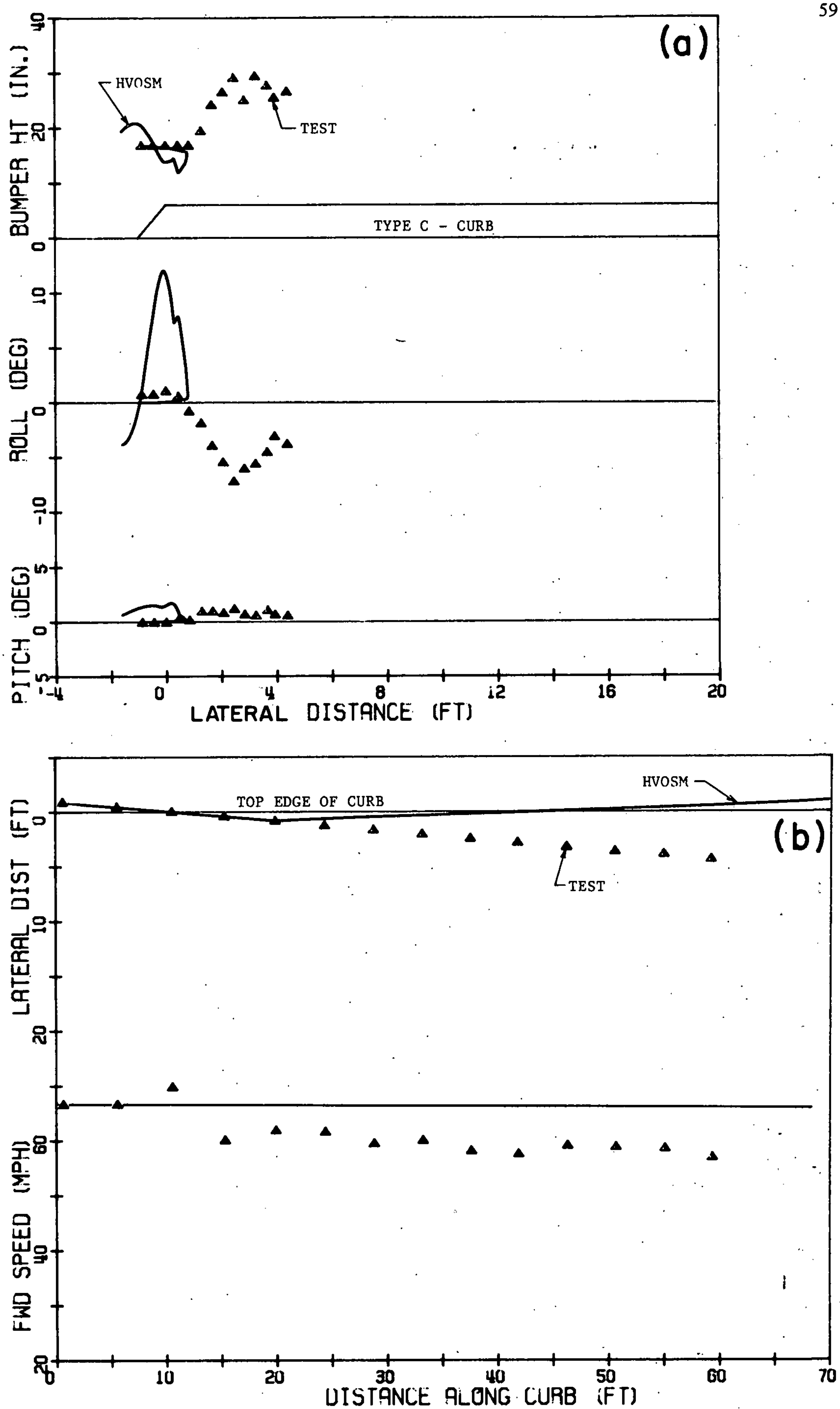


Figure D-16. Curb Type C, Test N-17 at 60-mph and 5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

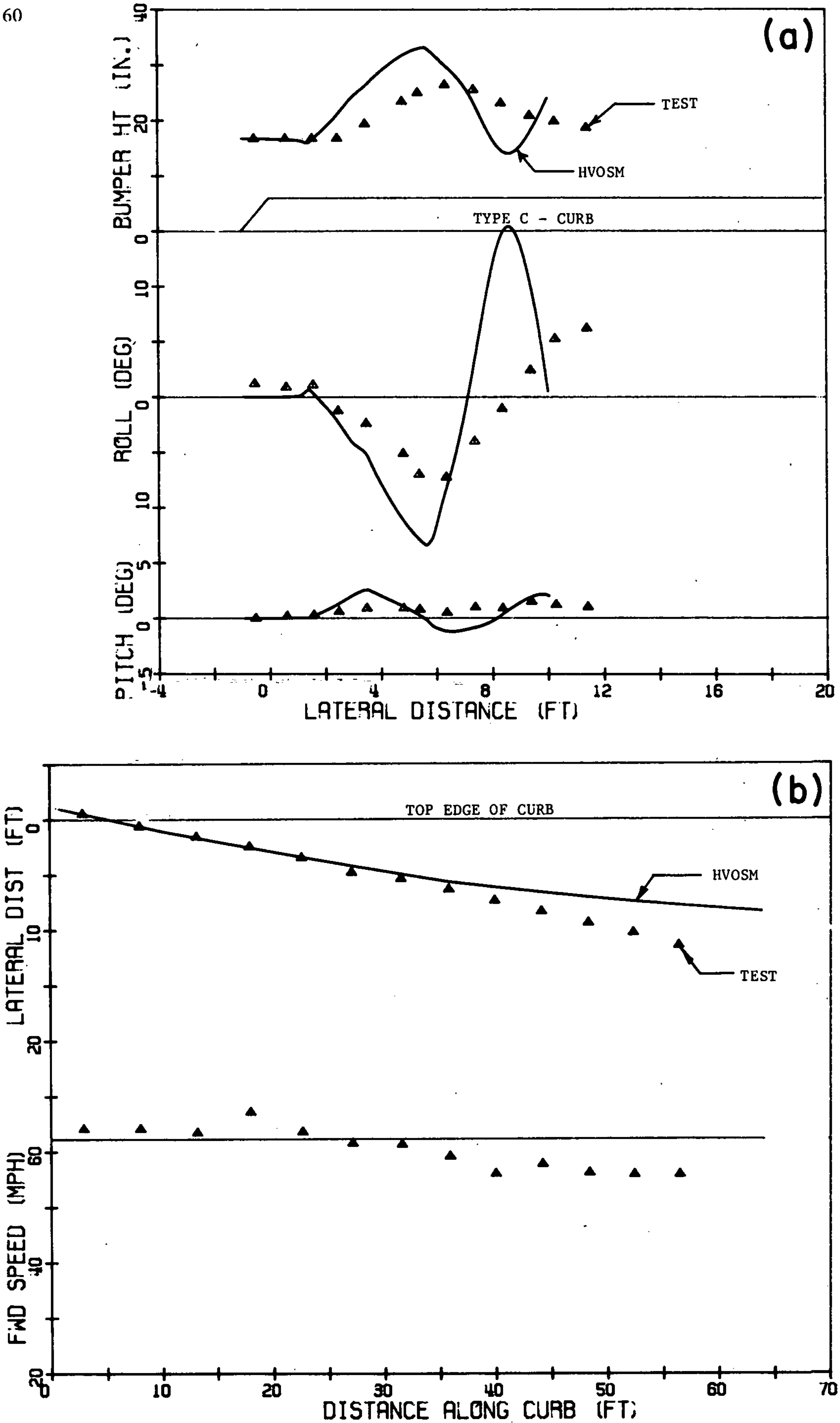
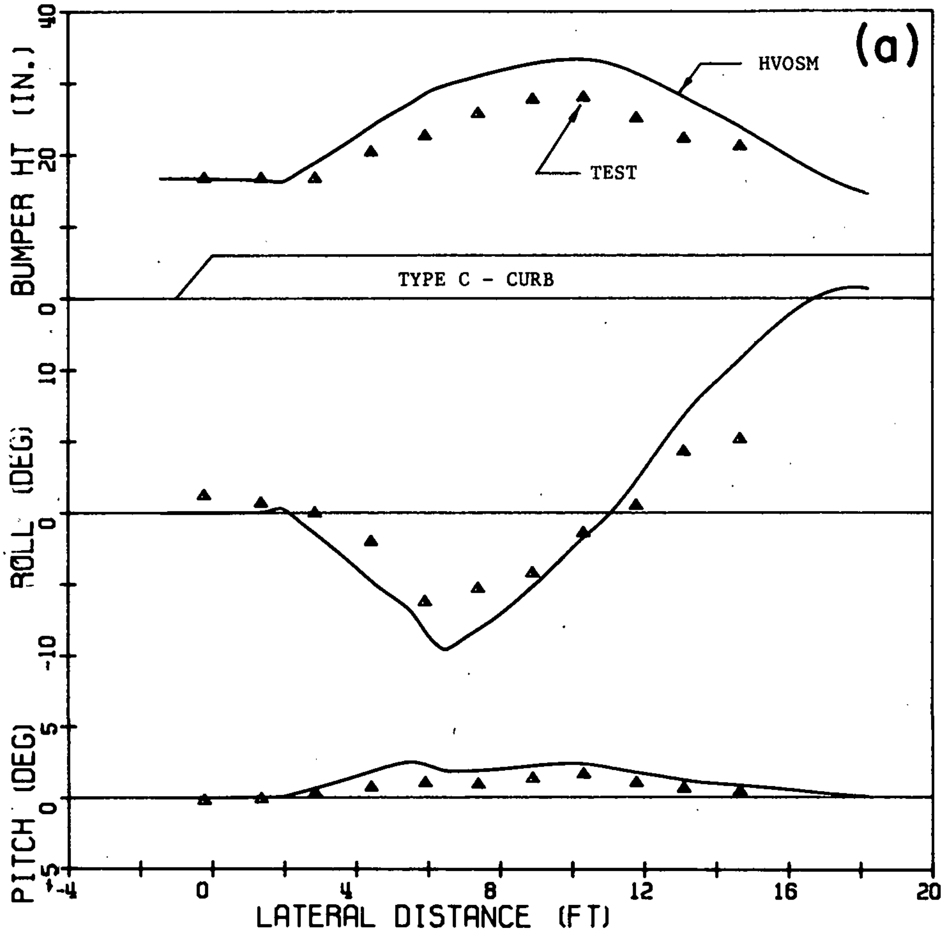


Figure D-17. Curb Type C, Test N-18 at 60-mph and 12.5-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.



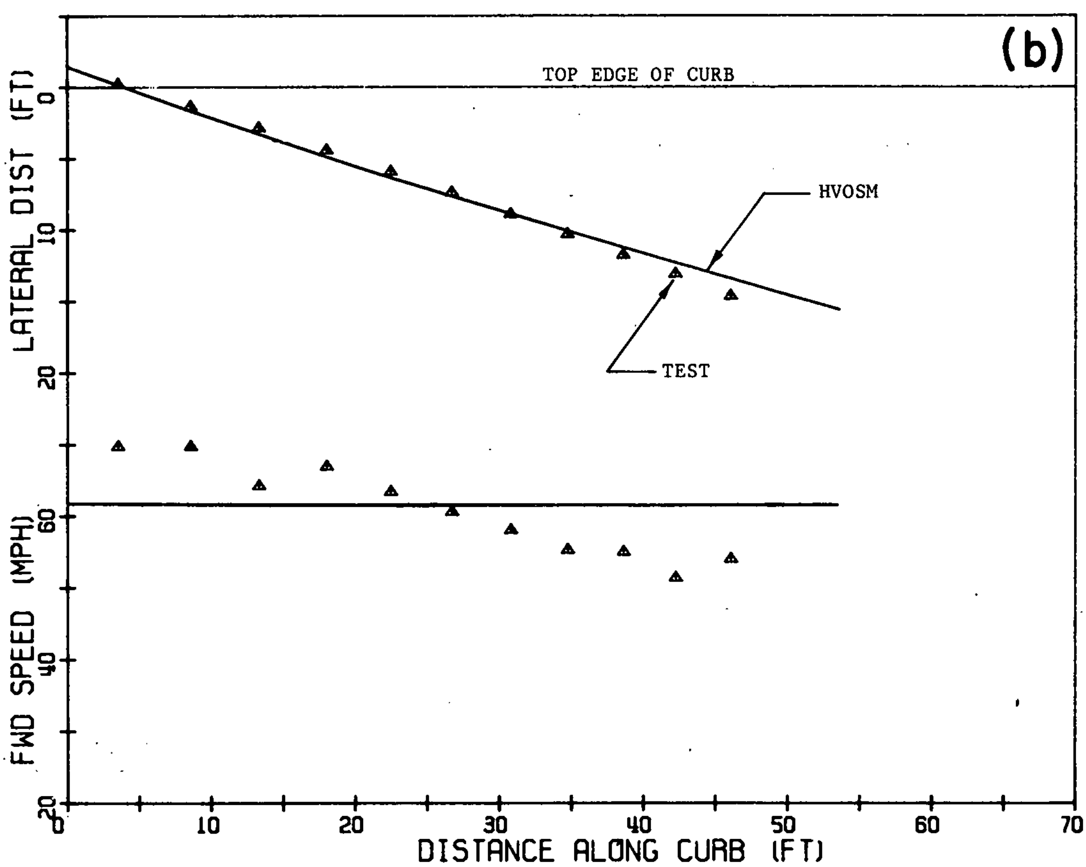


Figure D-18. Curb Type C, Test N-19 at 60-mph and 20-deg impact: (a) vehicle roll, pitch, and bumper rise; (b) vehicle speed and path.

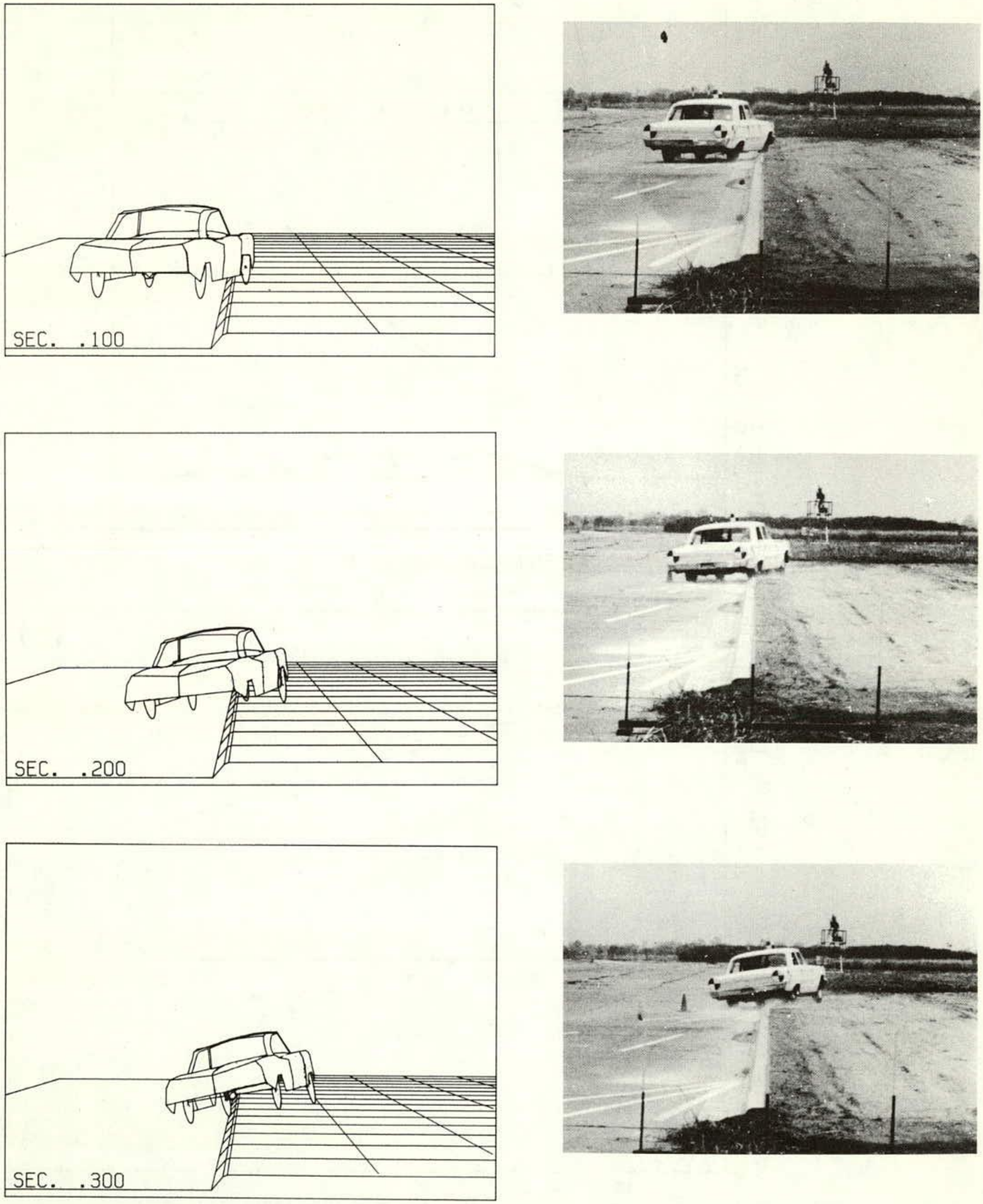
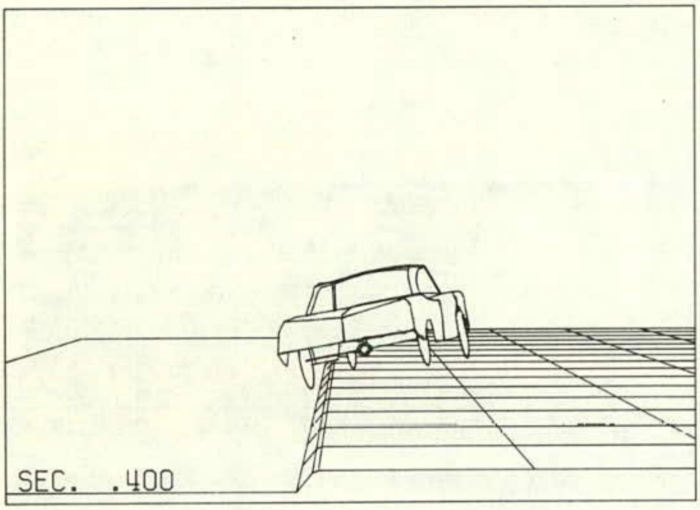
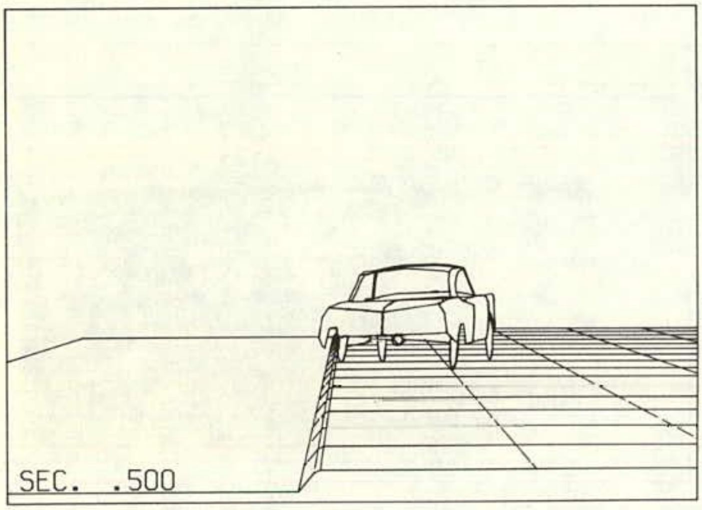


Figure D-19. Photographic comparison of Test N-7 HVOSM vehicle behavior with that of the full-scale-test vehicle on impact with curb Type E at 60 mph and a 12.5-deg angle in identical time sequences.





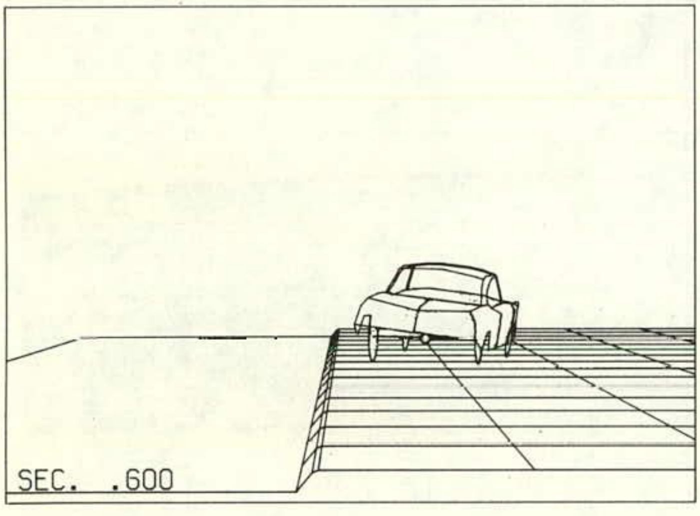


Figure D-19. (*Continued*).

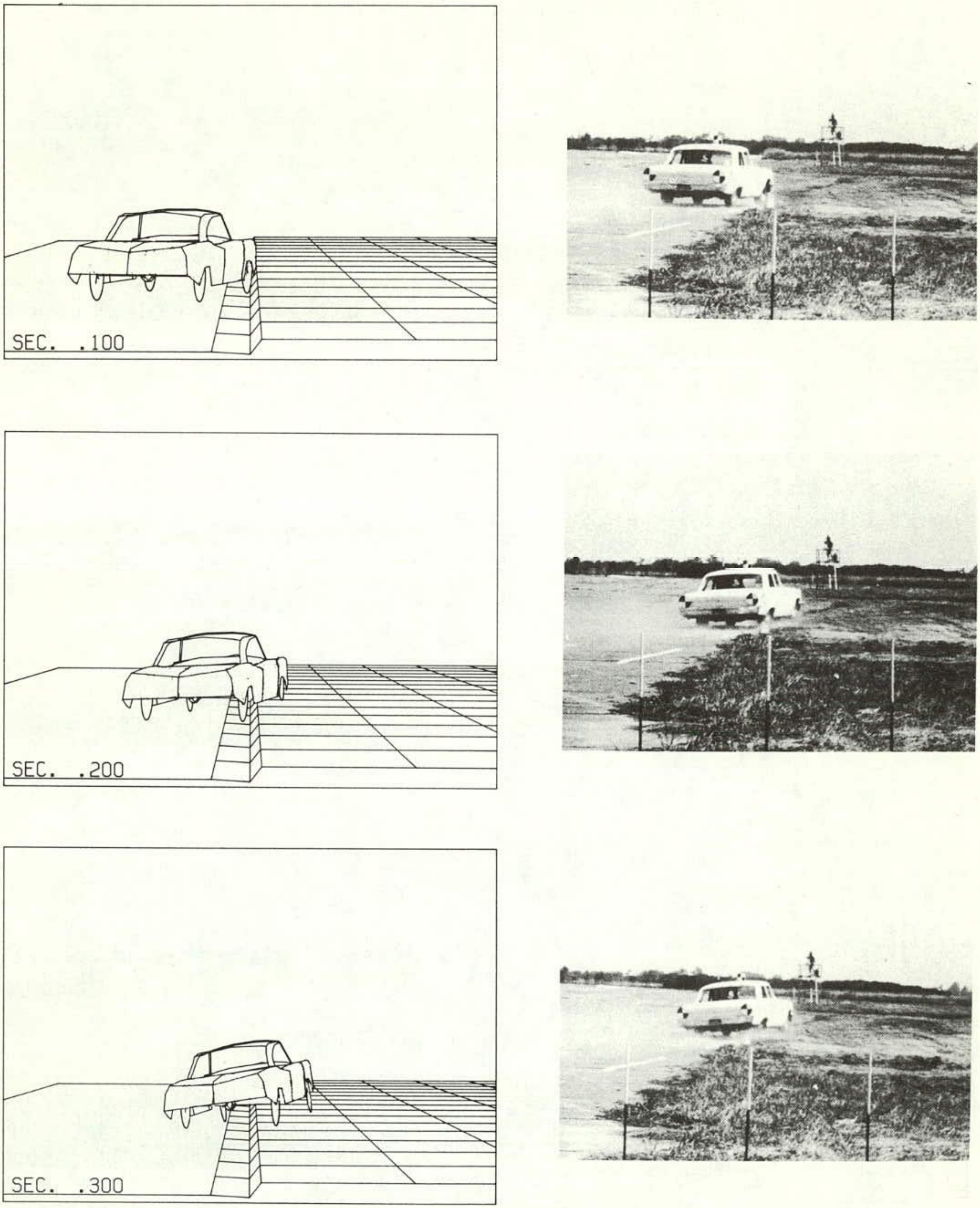


Figure D-20. Photographic comparison of Test N-18 HVOSM vehicle behavior with that of the full-scale-test vehicle on impact with curb Type C at 60 mph and a 12.5-deg angle in identical time sequences.

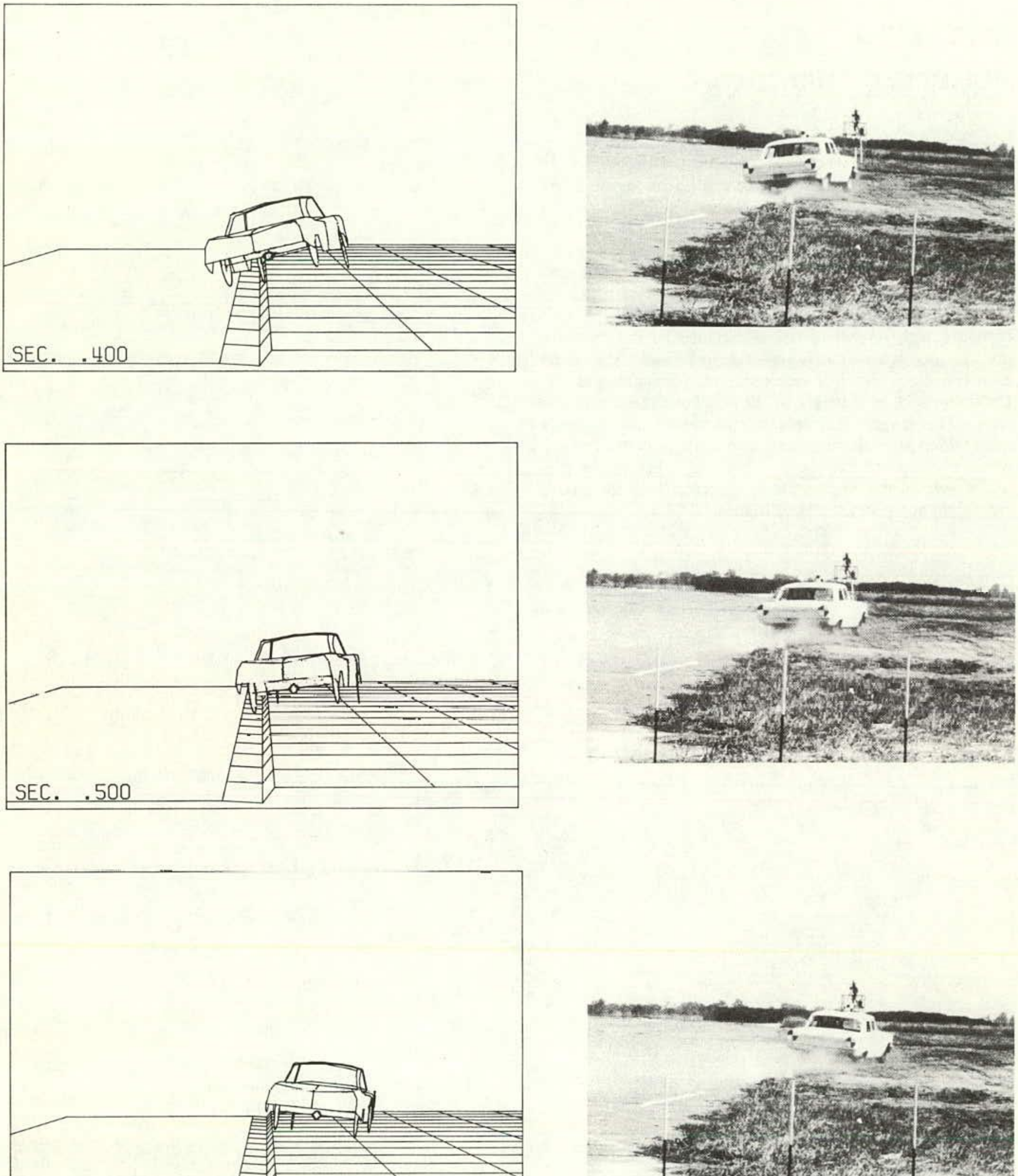


Figure D-20. (Continued).

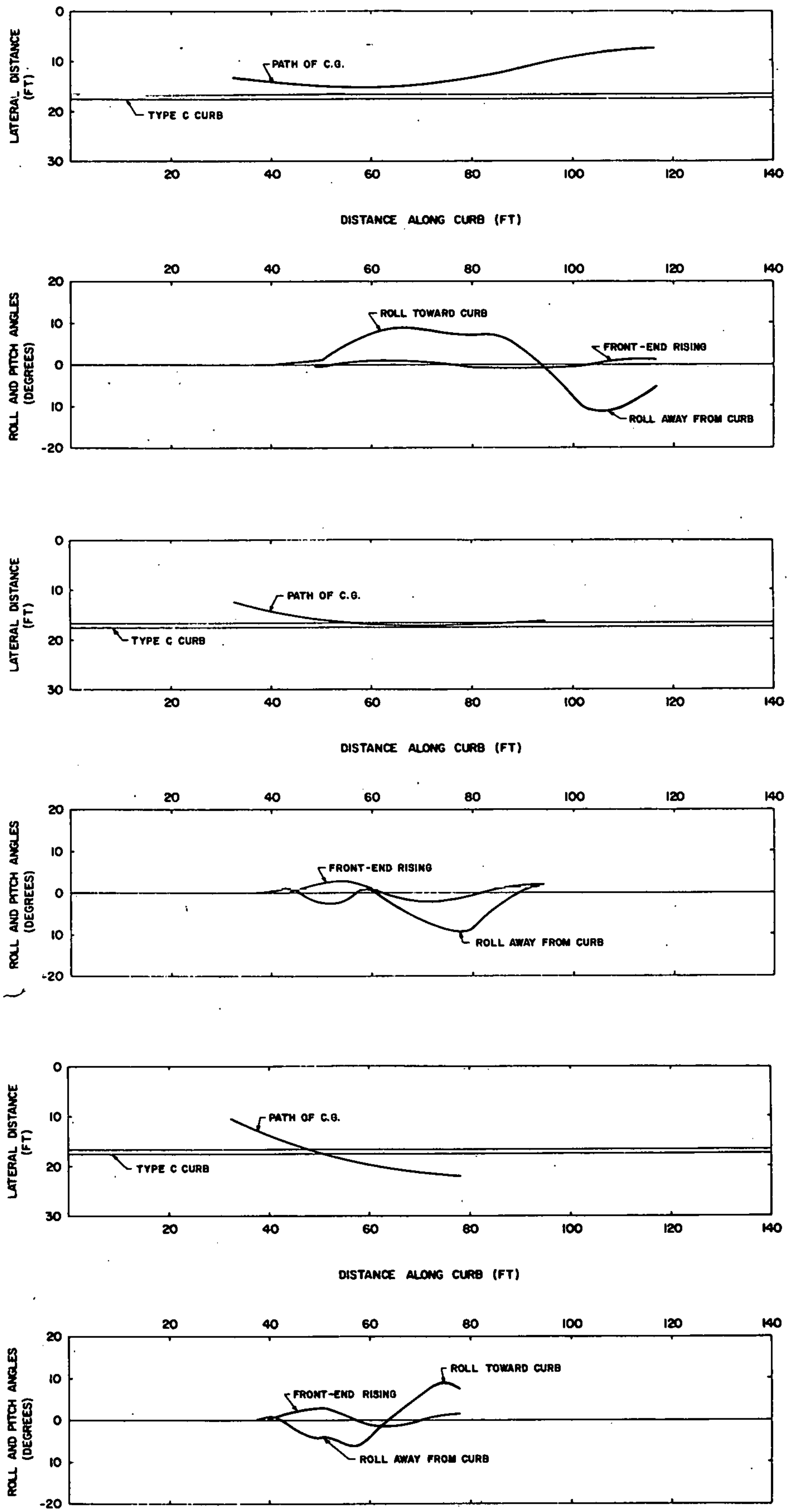
APPENDIX E

PARAMETRIC STUDY DATA

Included in this appendix are Figures E-1 through E-20 that show vehicle response characteristics for all curb impacts simulated in the parameter study. The data are categorized according to the four curbs (i.e., Types C, E, H, and X) studied.

Each category contains plots of vehicle path, roll, and pitch with respect to distance along the curb face. Also for each curb category, plots of vehicle trajectory (front bumper) with respect to lateral distance behind the curb are included where curb cross-over occurred. Shown on each trajectory plot is a reference line (designated as 27″ traffic barrier) at a height of 27 in. above the top of the curb. This height, representative of the guardrail height most widely used throughout the country, is shown in each figure so that one may easily determine whether the predicted vertical rise of the vehicle is greater than the guardrail height at a selected offset distance.

TYPE C CURB



5-deg angle

12.5-deg angle

20-deg angle

Figure E-1. Vehicle path, roll, and pitch for Type C curb with simulated impact of 30 mph.

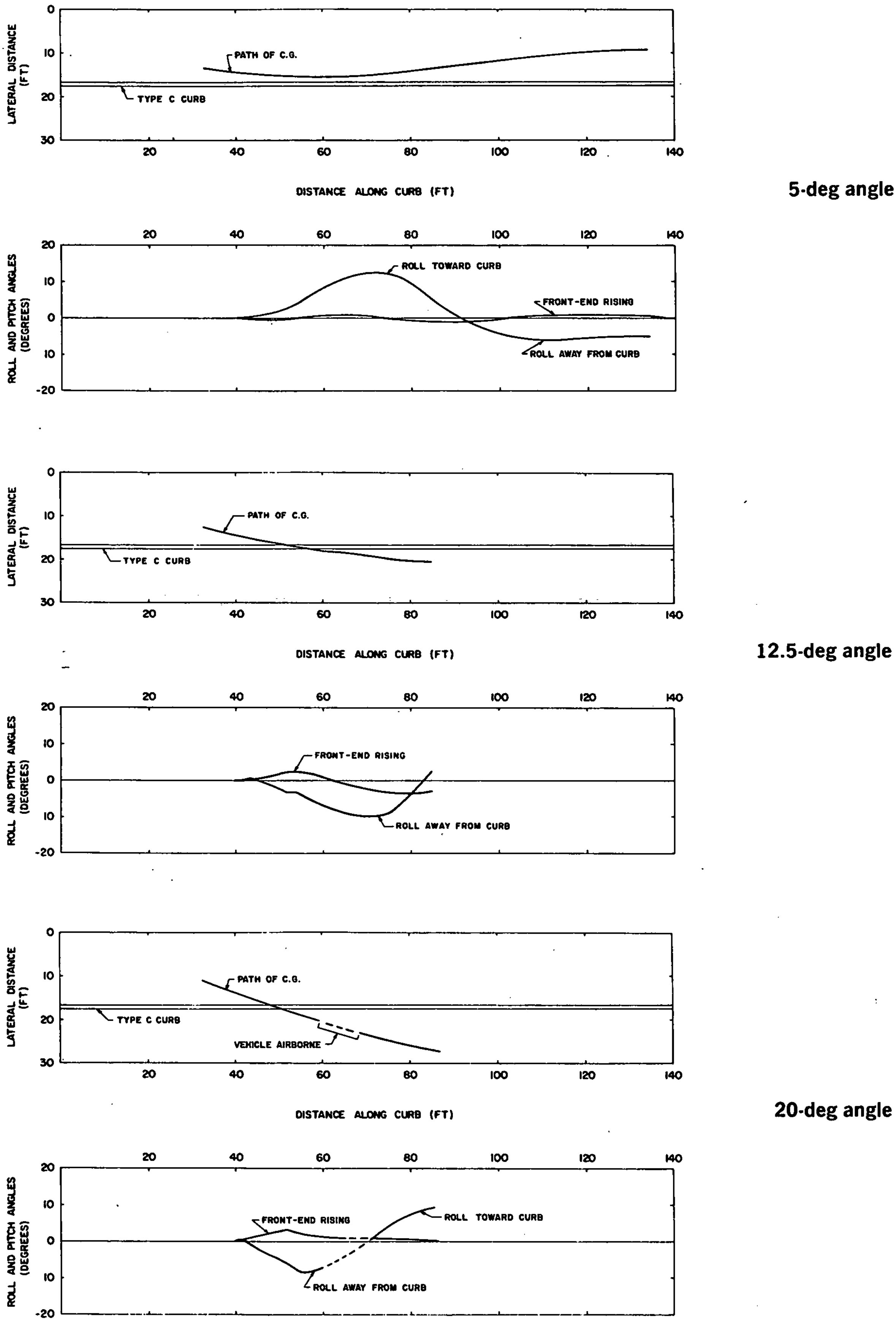


Figure E-2. Vehicle path, roll, and pitch for Type C curb with simulated impact of 45 mph.

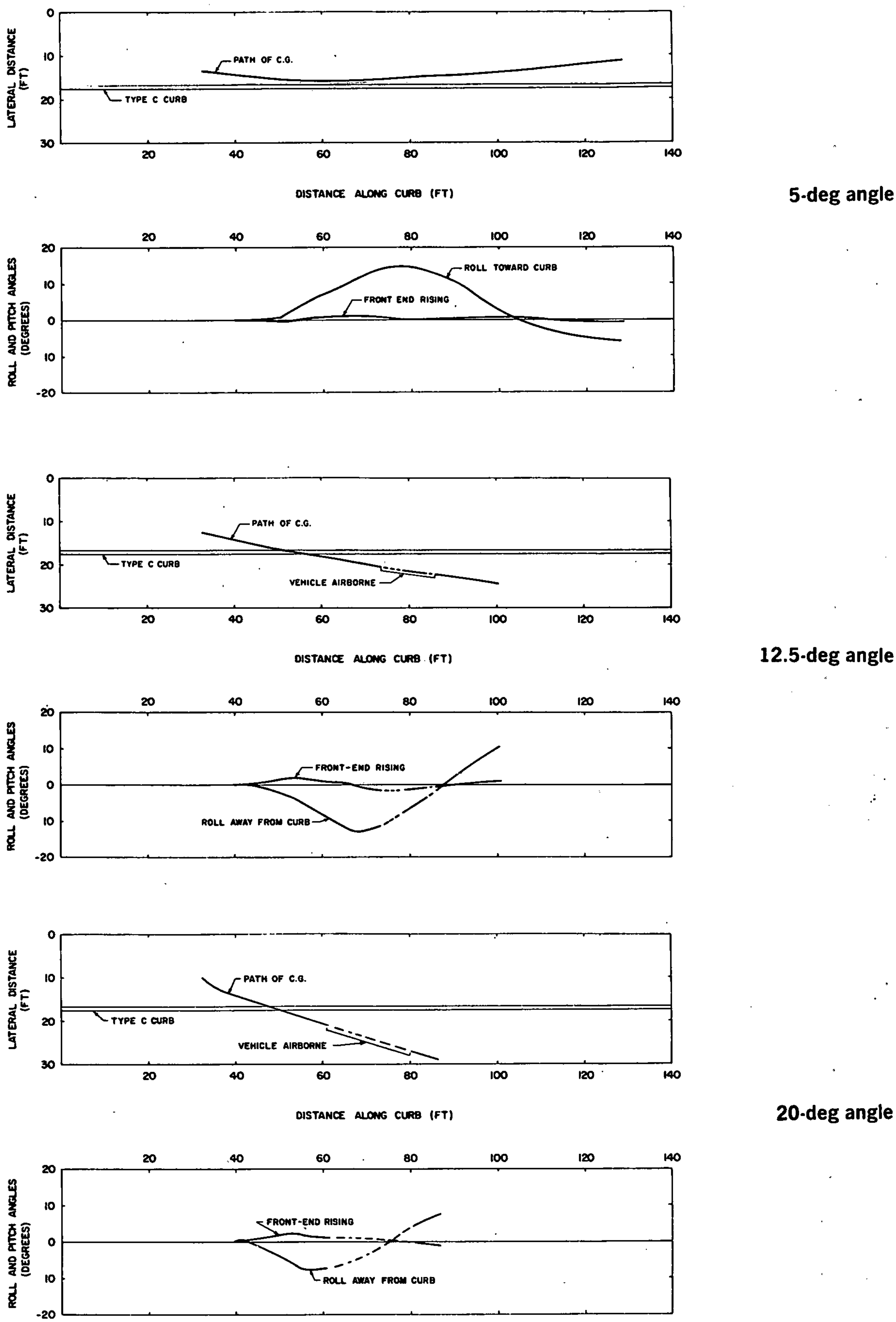


Figure E-3. Vehicle path, roll, and pitch for Type C curb with simulated impact of 60 mph.

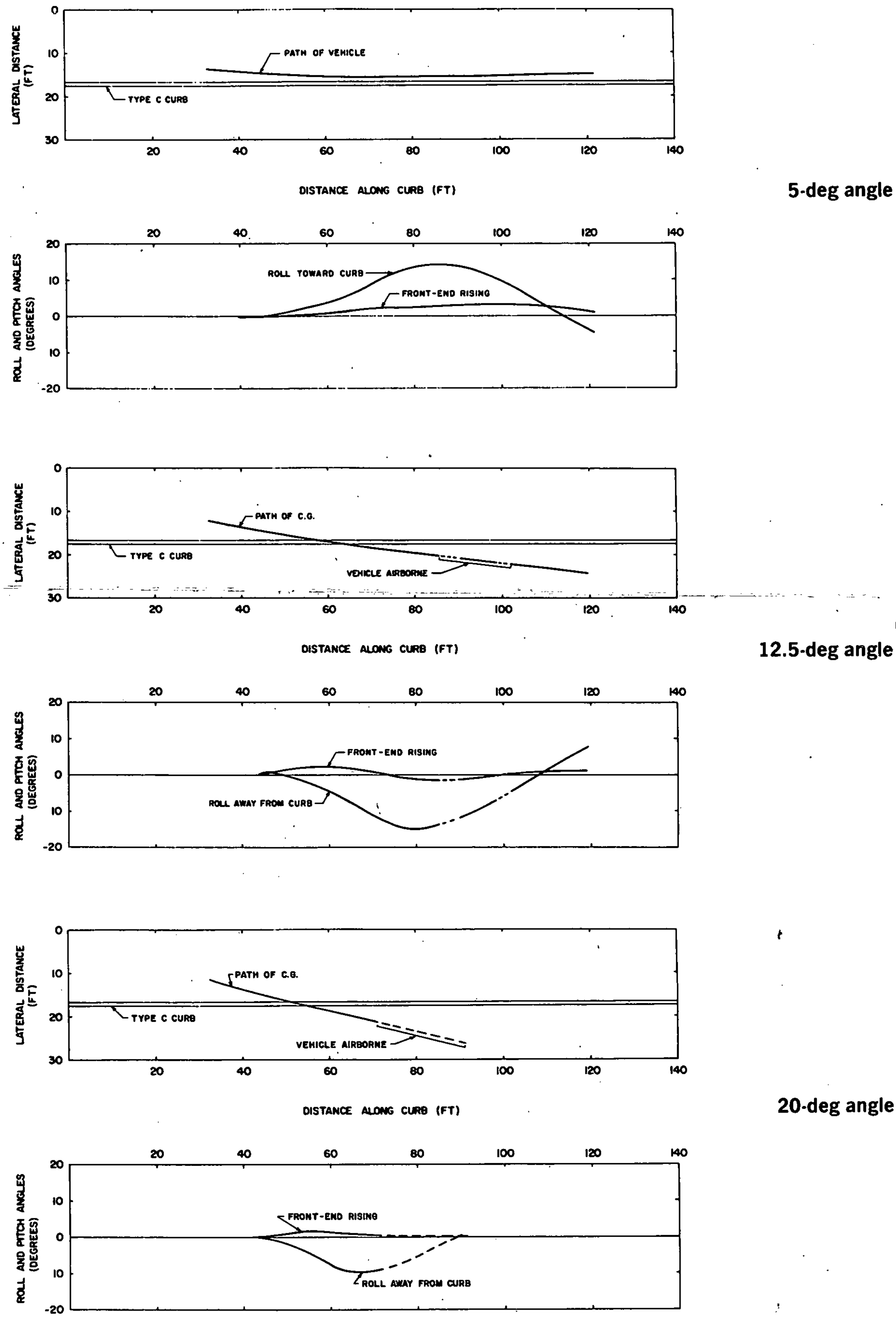


Figure E-4. Vehicle path, roll, and pitch for Type C curb with simulated impact of 75 mph.

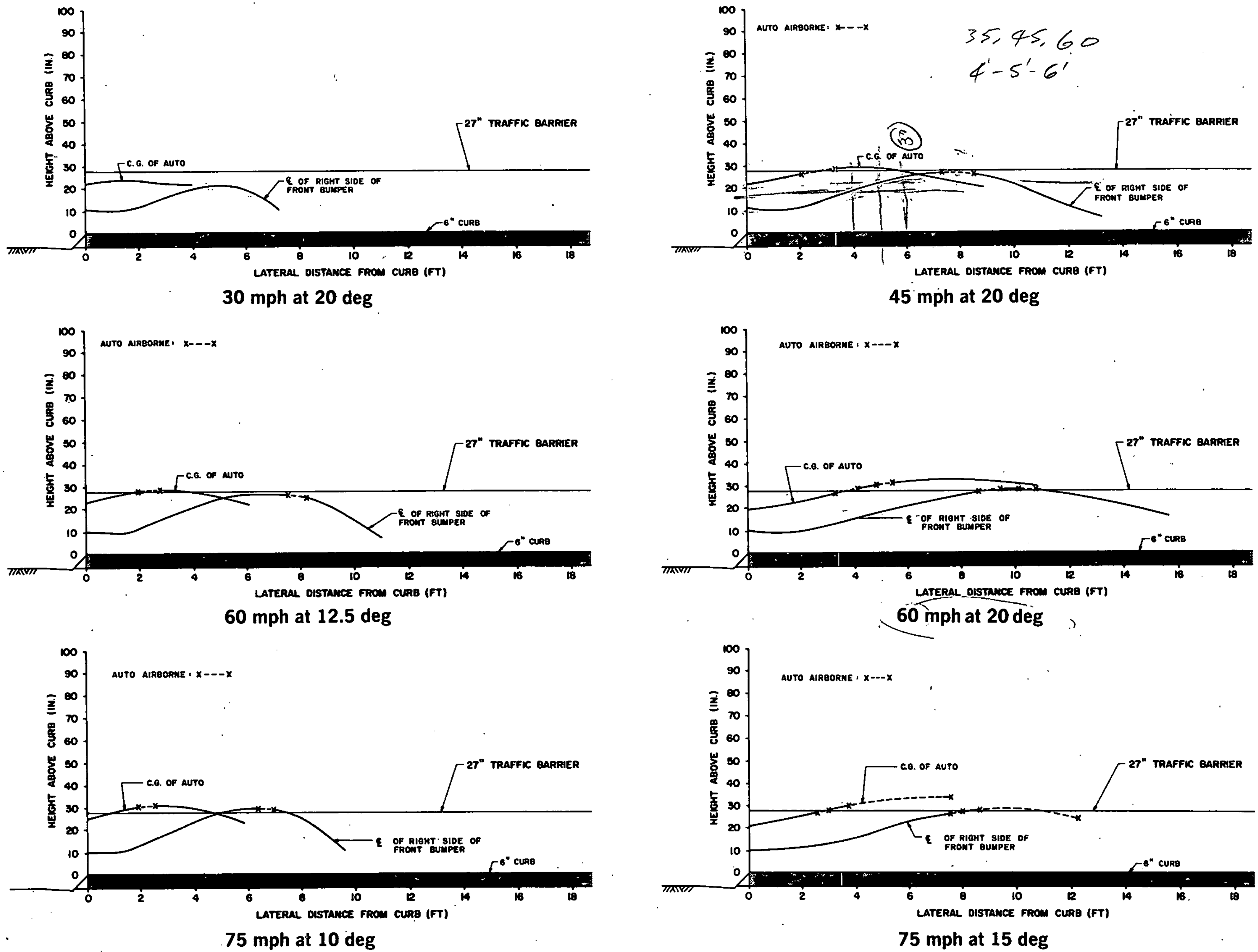
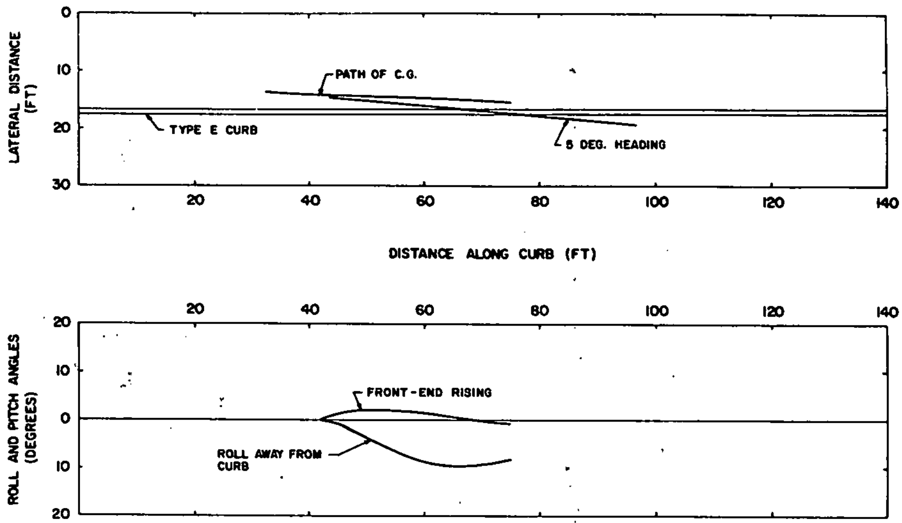
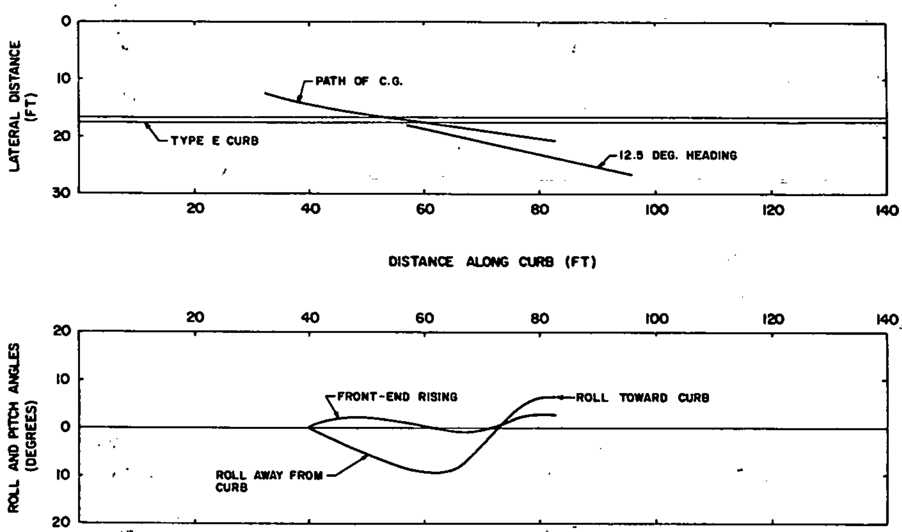


Figure E-5. Vertical rise of vehicle at various impact speeds and angles for Type C curb.

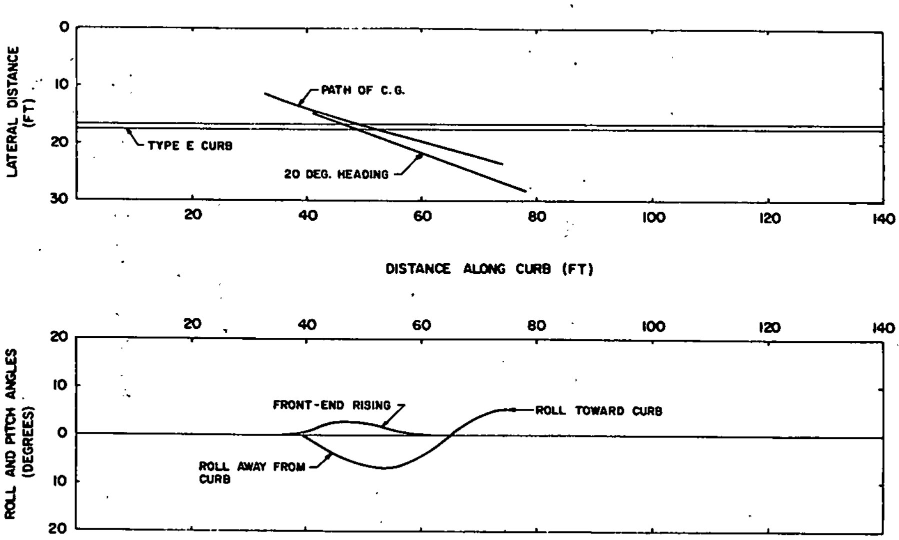
TYPE E CURB



5-deg angle

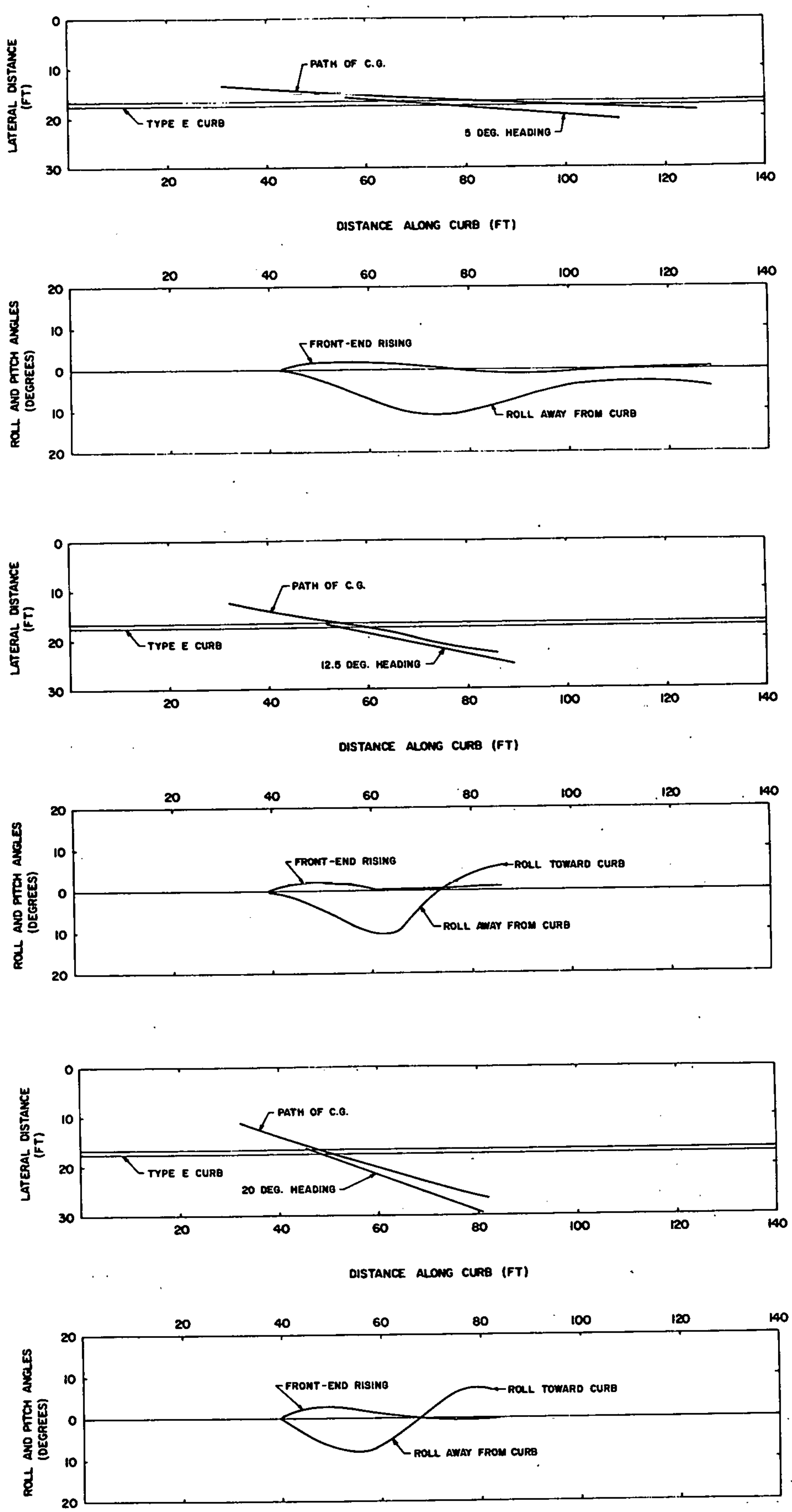


12.5-deg angle



20-deg angle

Figure E-6. Vehicle path, roll, and pitch for Type E curb with simulated impact of 30 mph.

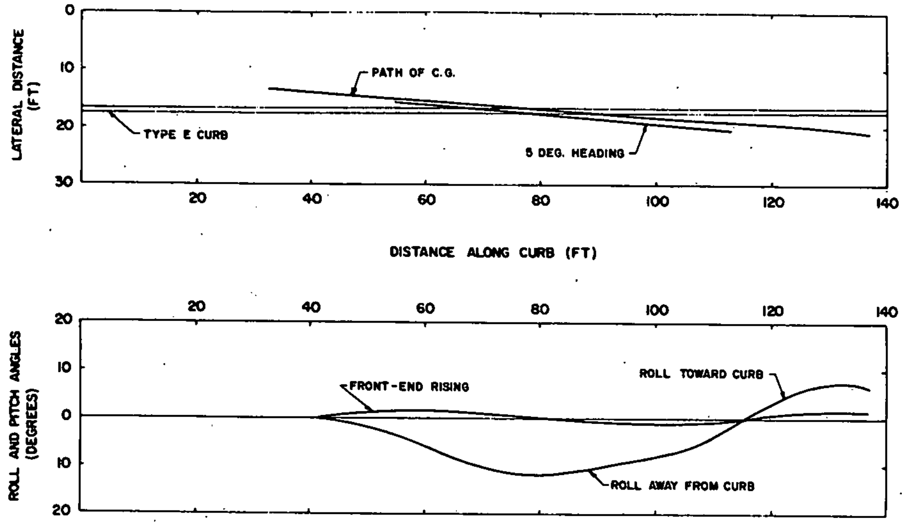


5-deg angle

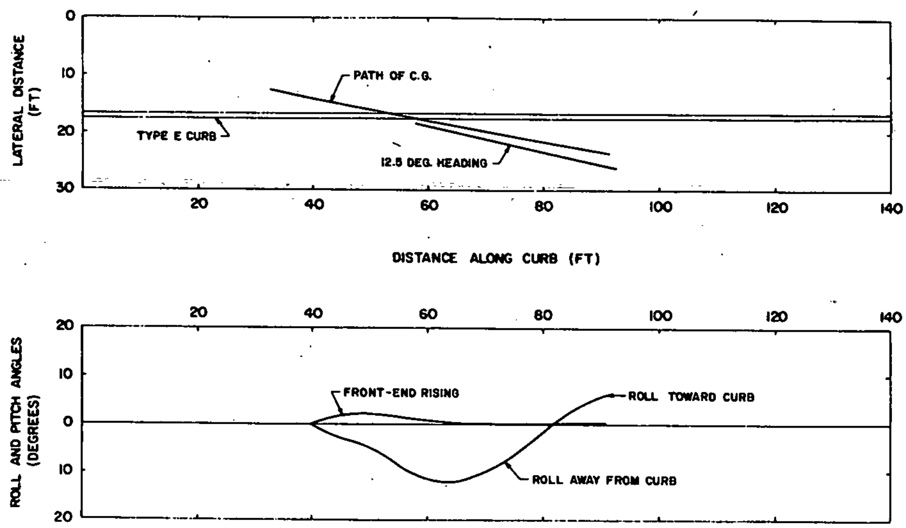
12.5-deg angle

20-deg angle

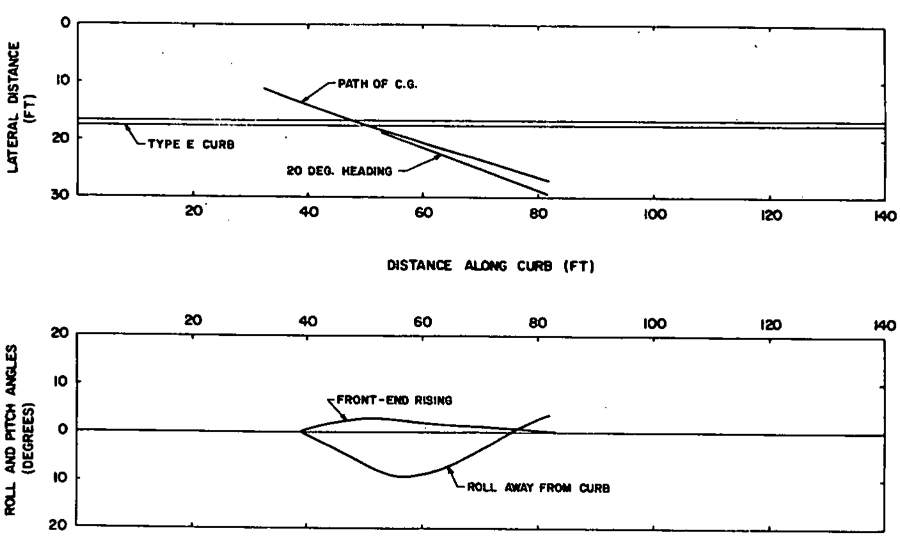
Figure E-7. Vehicle path, roll, and pitch for Type E curb with simulated impact of 45 mph.



5-deg angle



12.5-deg angle



20-deg angle

Figure E-8. Vehicle path, roll, and pitch for Type E curb with simulated impact of 60 mph.

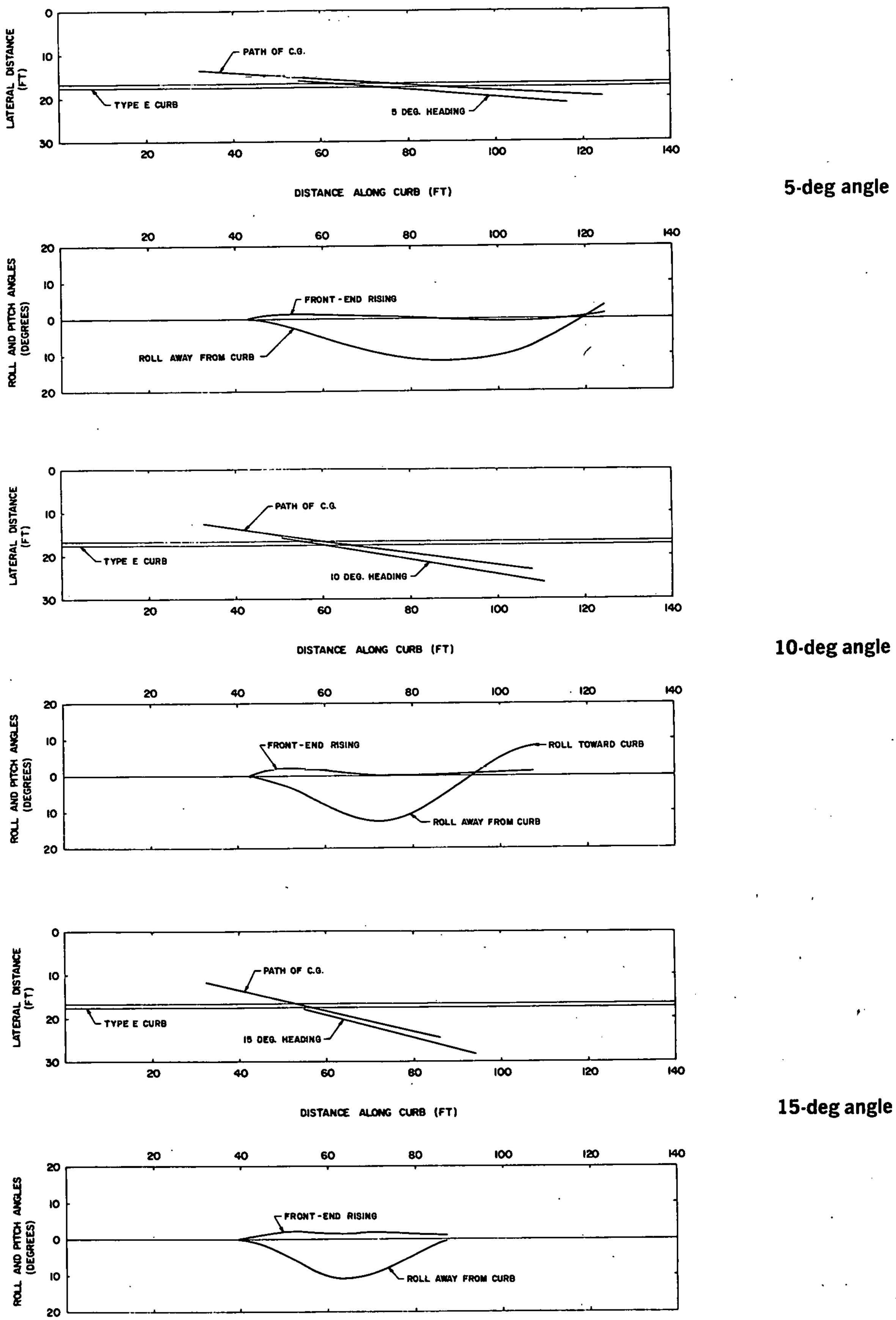
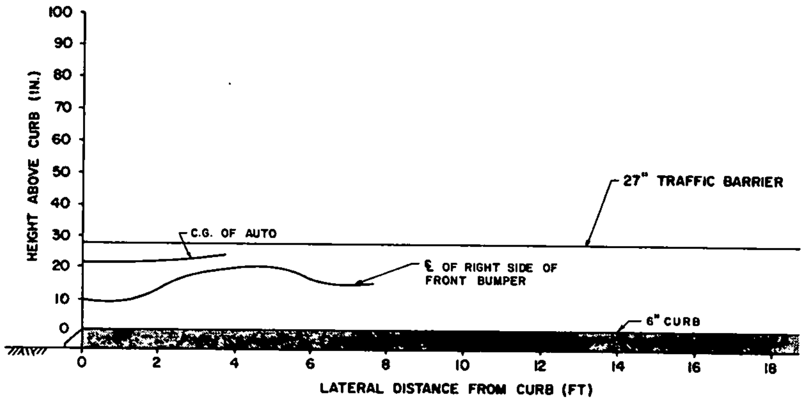
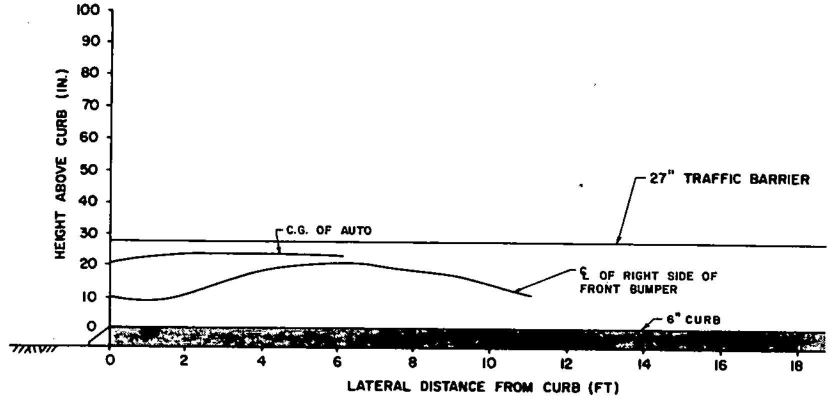


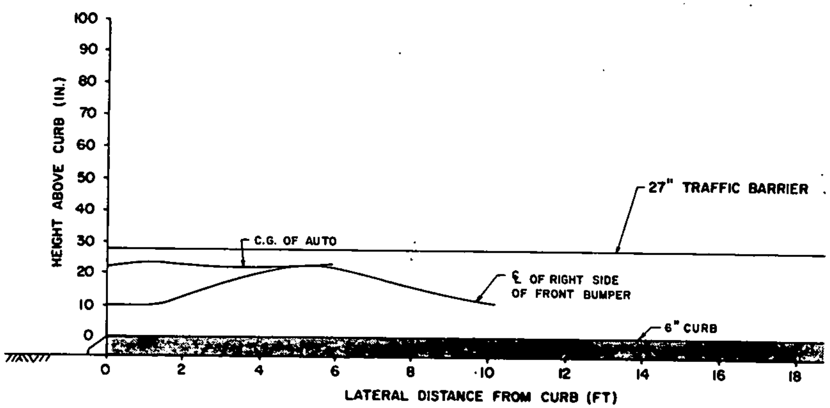
Figure E-9. Vehicle path, roll, and pitch for Type E curb with simulated impact of 75 mph.



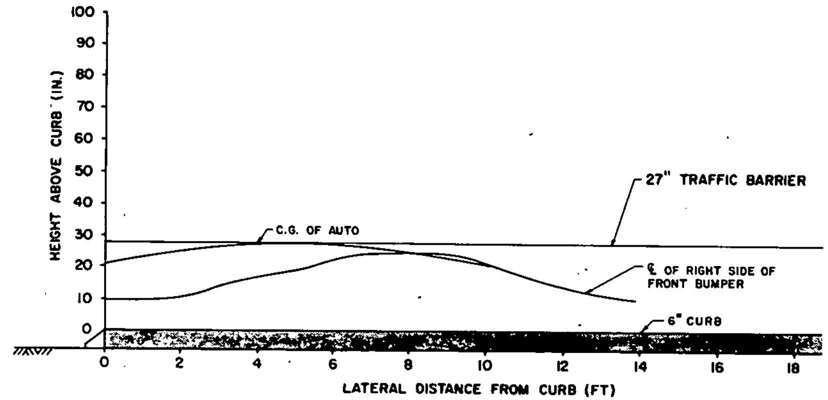
30 mph at 12.5 deg



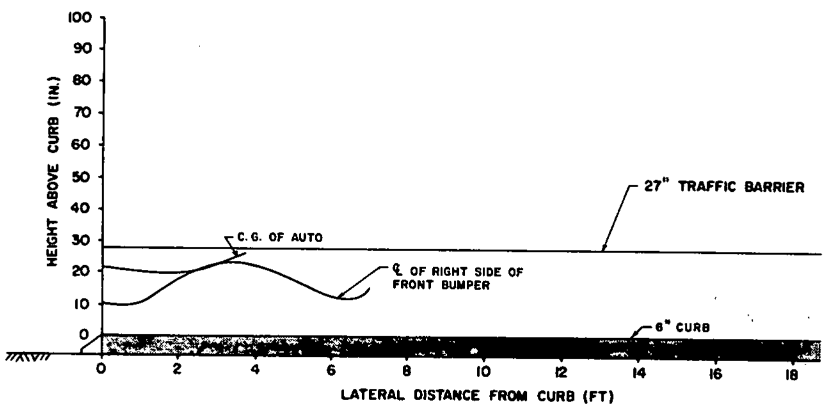
30 mph at 20 deg



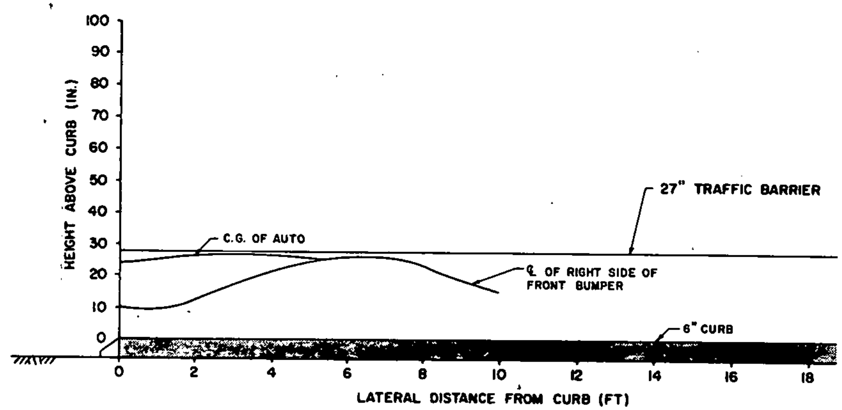
45 mph at 12.5 deg



45 mph at 20 deg



60 mph at 5 deg



60 mph at 12.5 deg

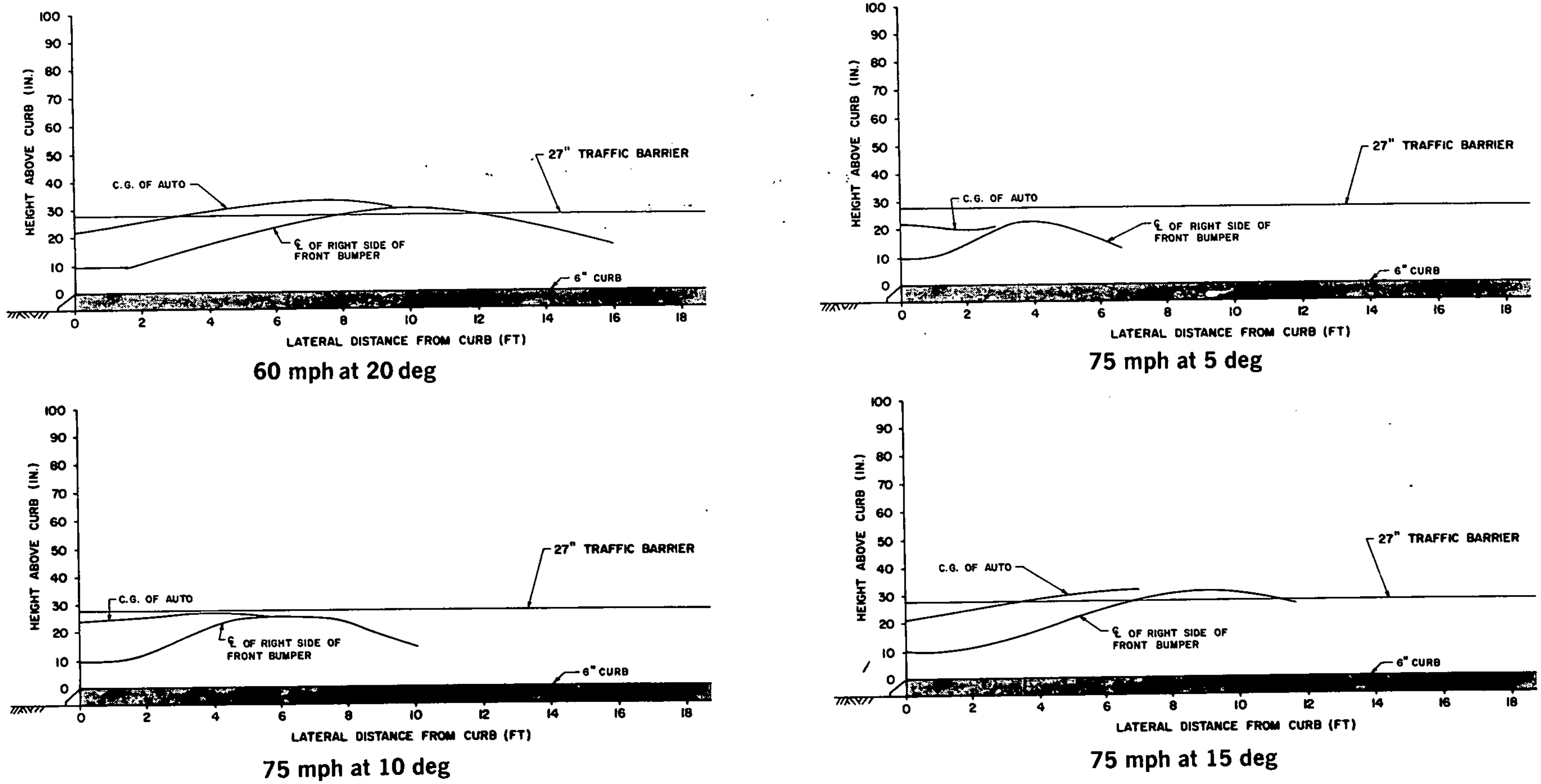


Figure E-10. Vertical rise of vehicle at various impact speeds and angles for Type E curb.

TYPE H CURB

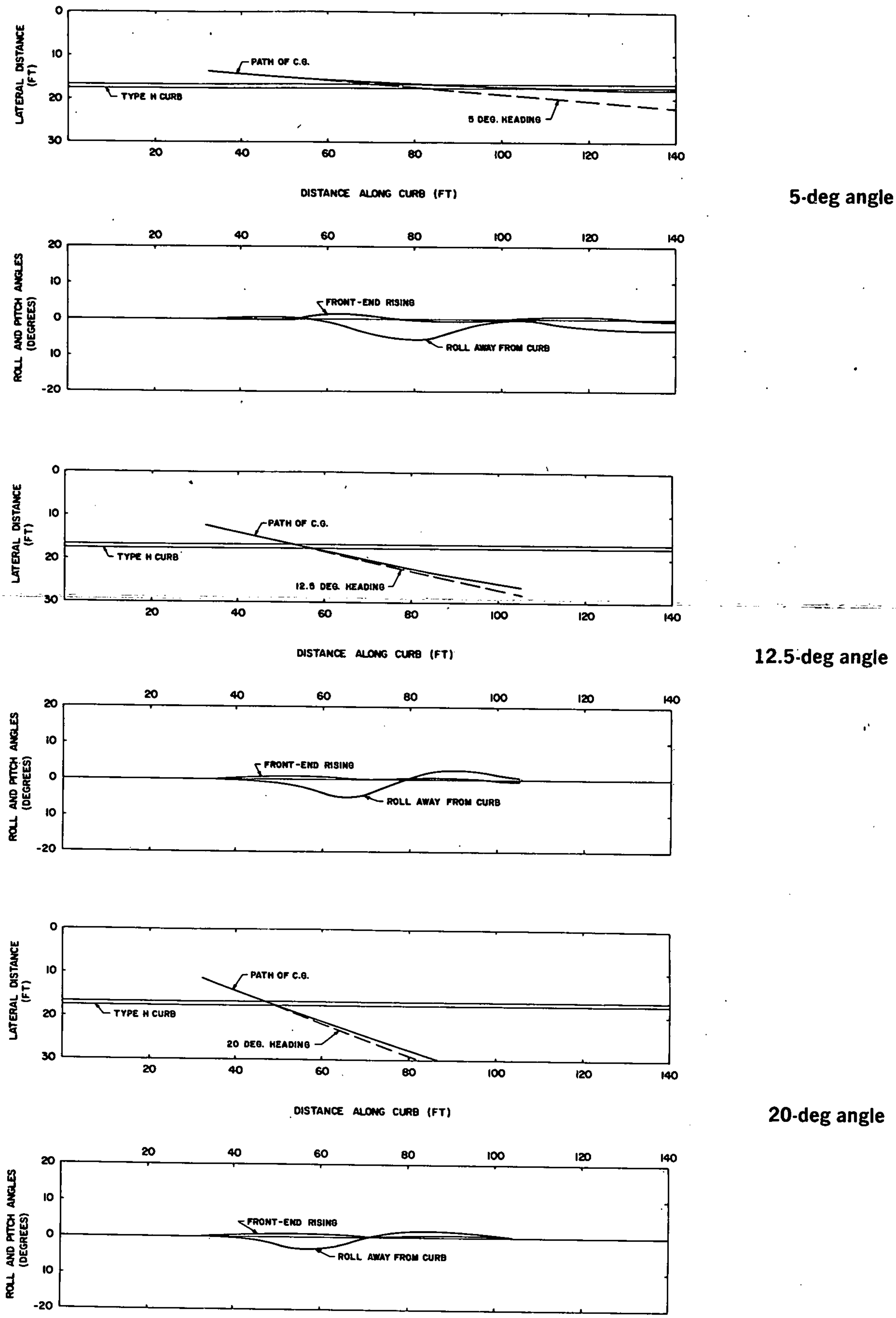
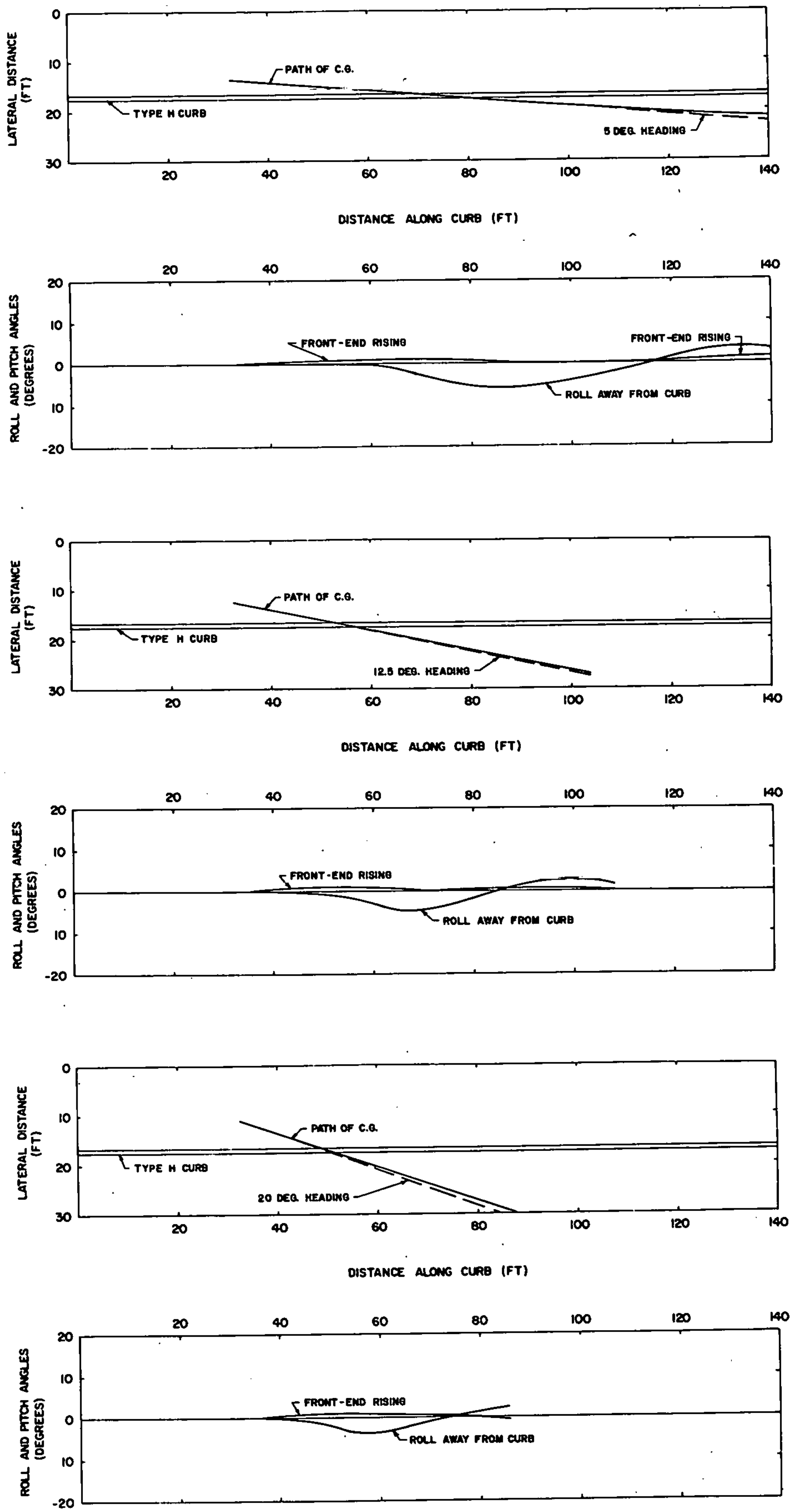


Figure E-11. Vehicle path, roll, and pitch for Type H curb with simulated impact of 30 mph.

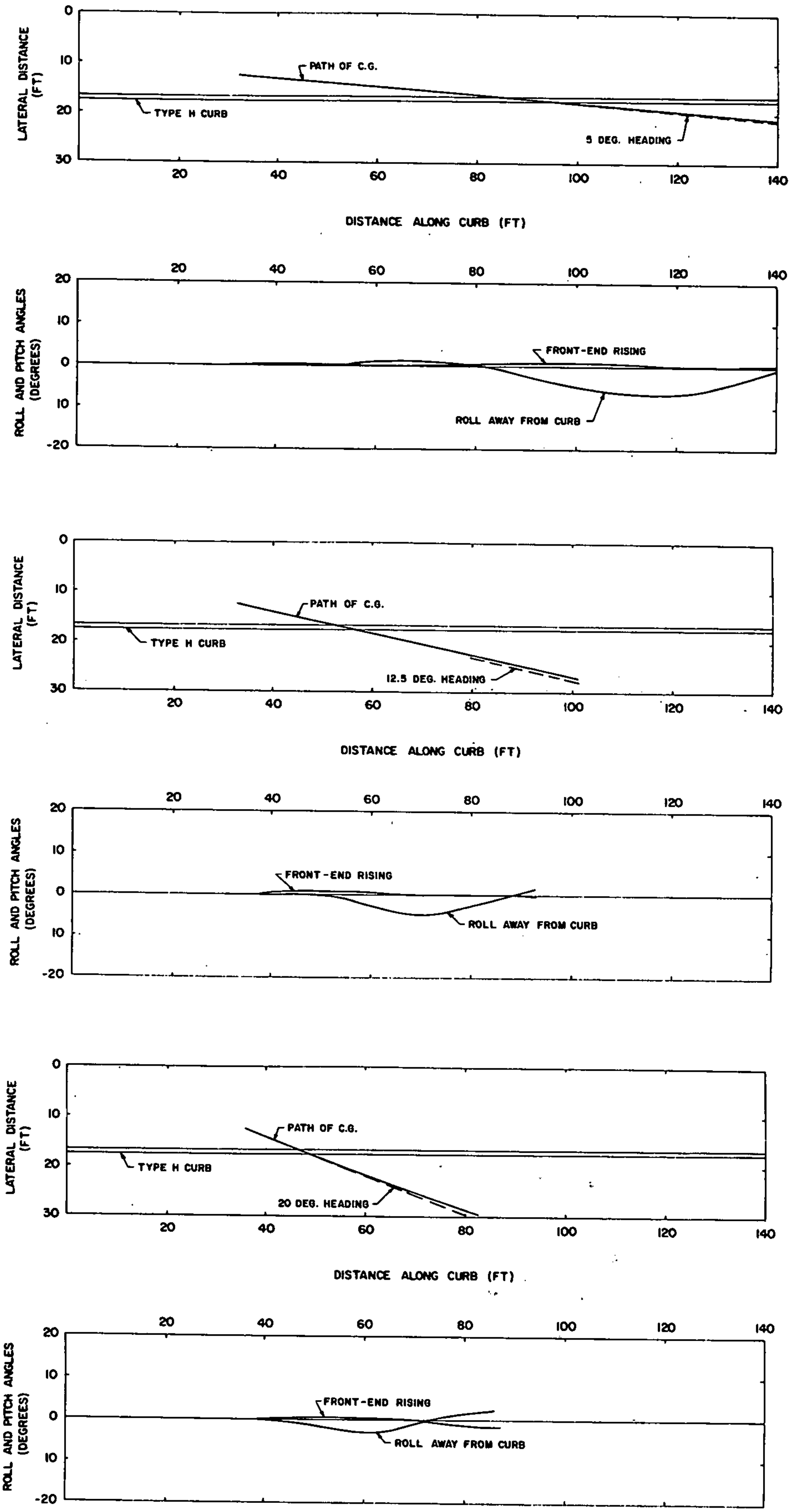


5-deg angle

12.5-deg angle

20-deg angle

Figure E-12. Vehicle path, roll, and pitch for Type H curb with simulated impact of 45 mph.



5-deg angle

12.5-deg angle

20-deg angle

Figure E-13. Vehicle path, roll, and pitch for Type H curb with simulated impact of 60 mph.

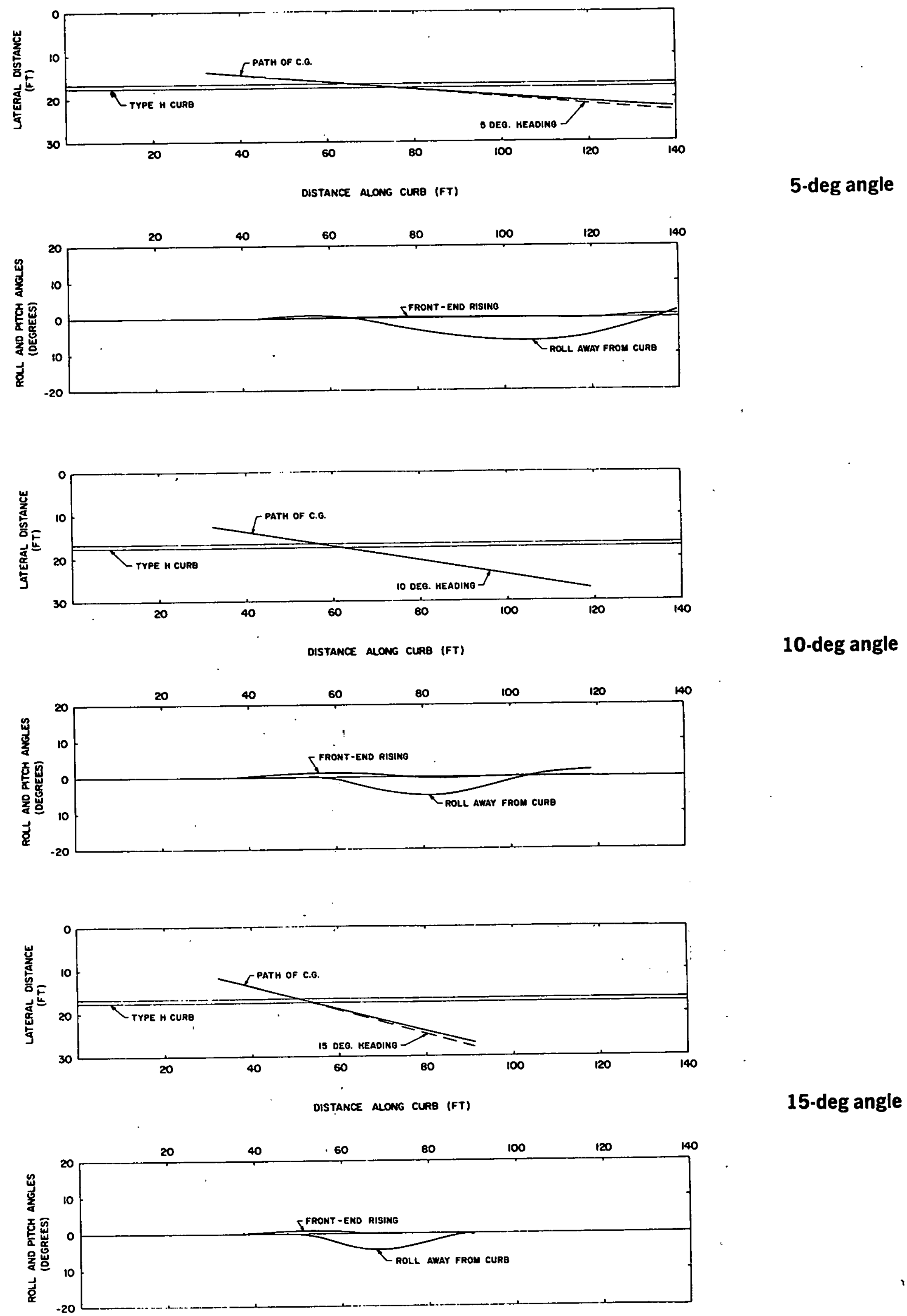


Figure E-14. Vehicle path, roll, and pitch for Type H curb with simulated impact of 75 mph.

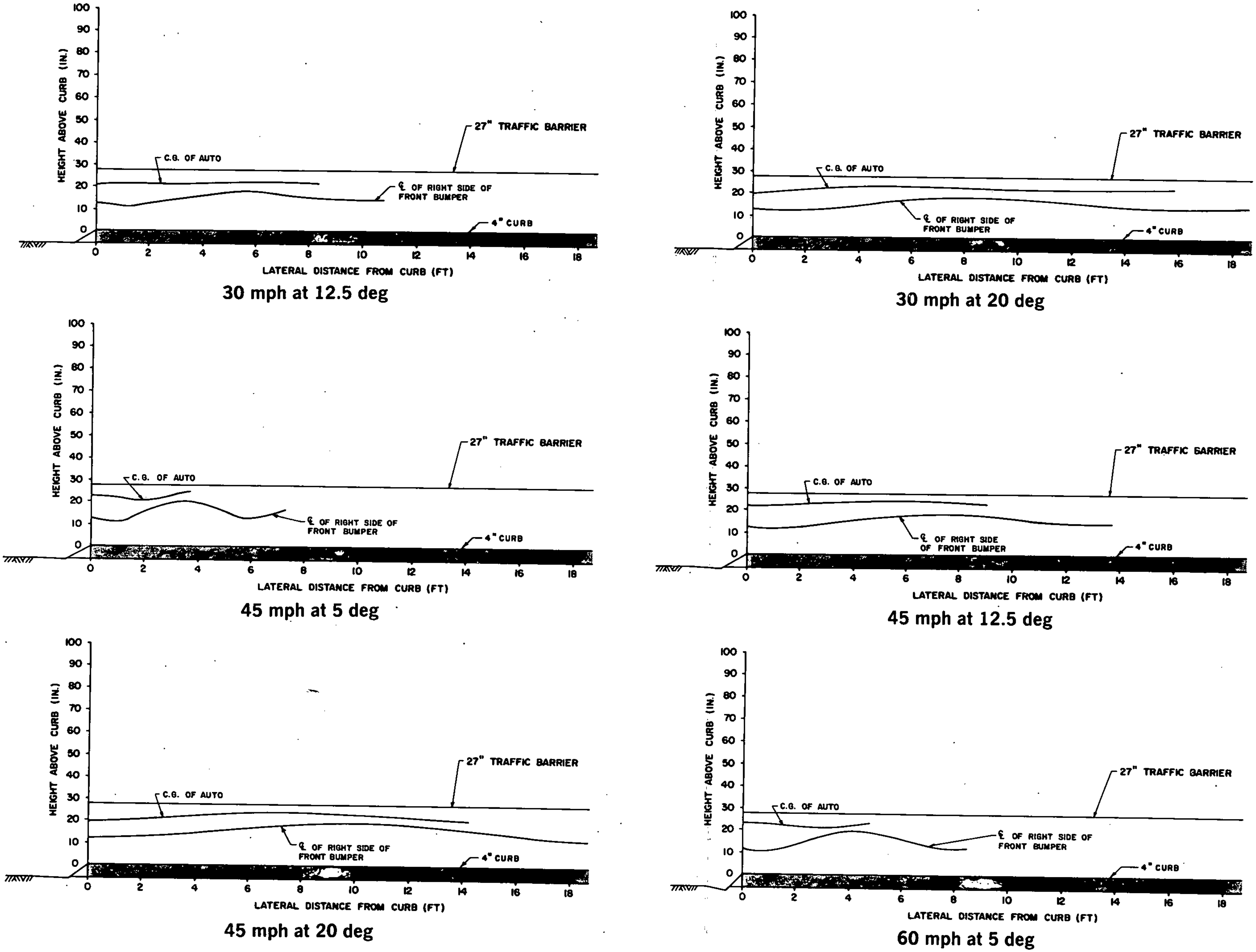
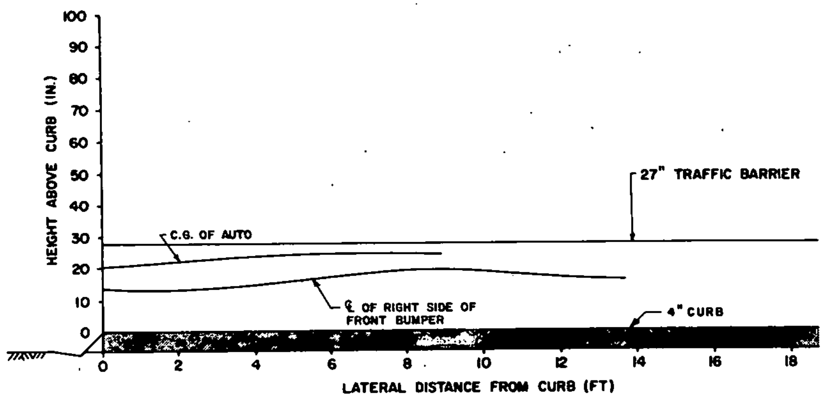
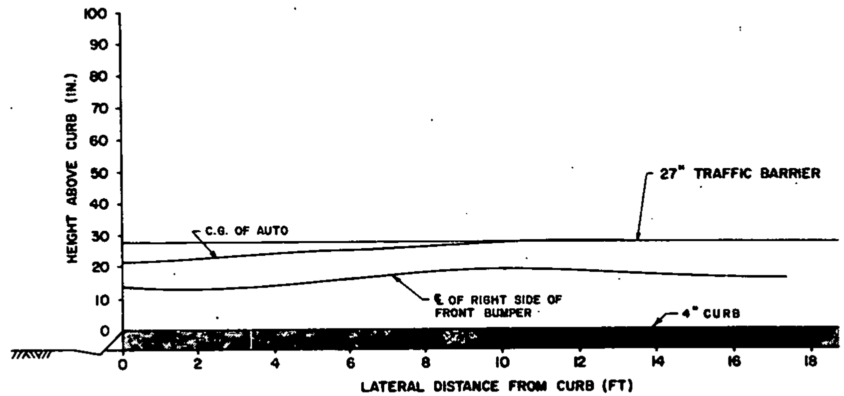


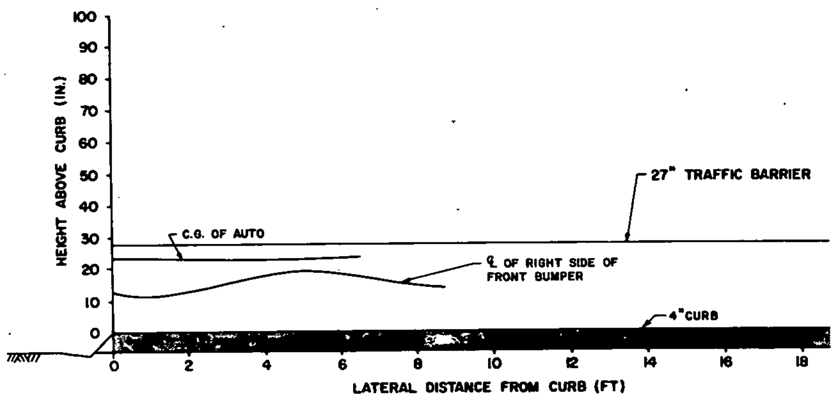
Figure E-15. Vertical rise of vehicle at various impact speeds and angles for Type H curb.



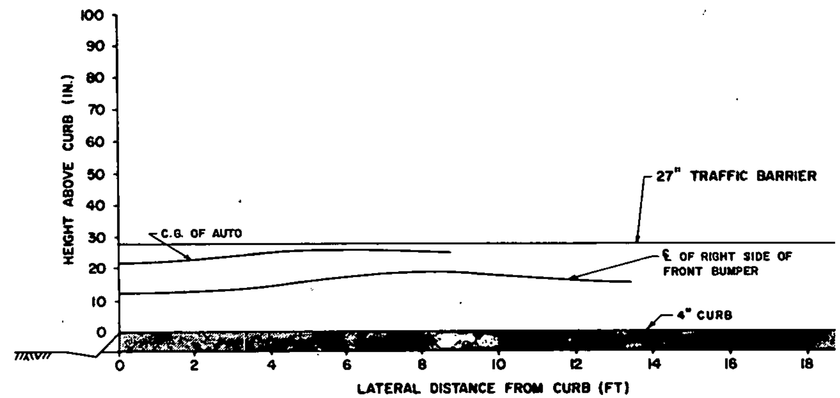
60 mph at 12.5 deg



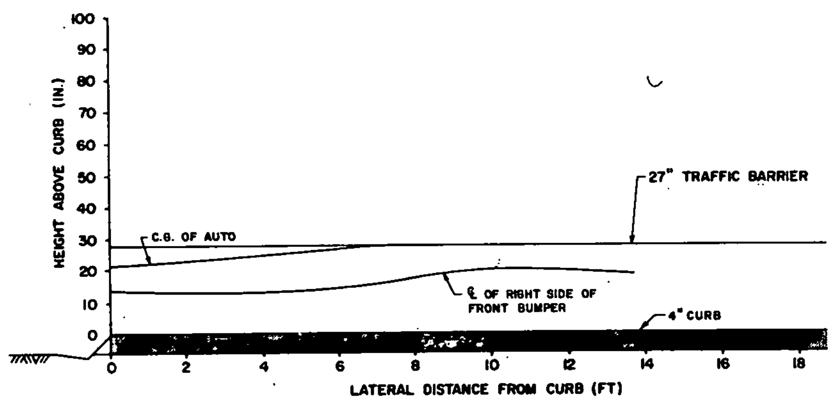
60 mph at 20 deg



75 mph at 5 deg



75 mph at 10 deg



75 mph at 15 deg

Figure E-15. (Continued)

TYPE X CURB

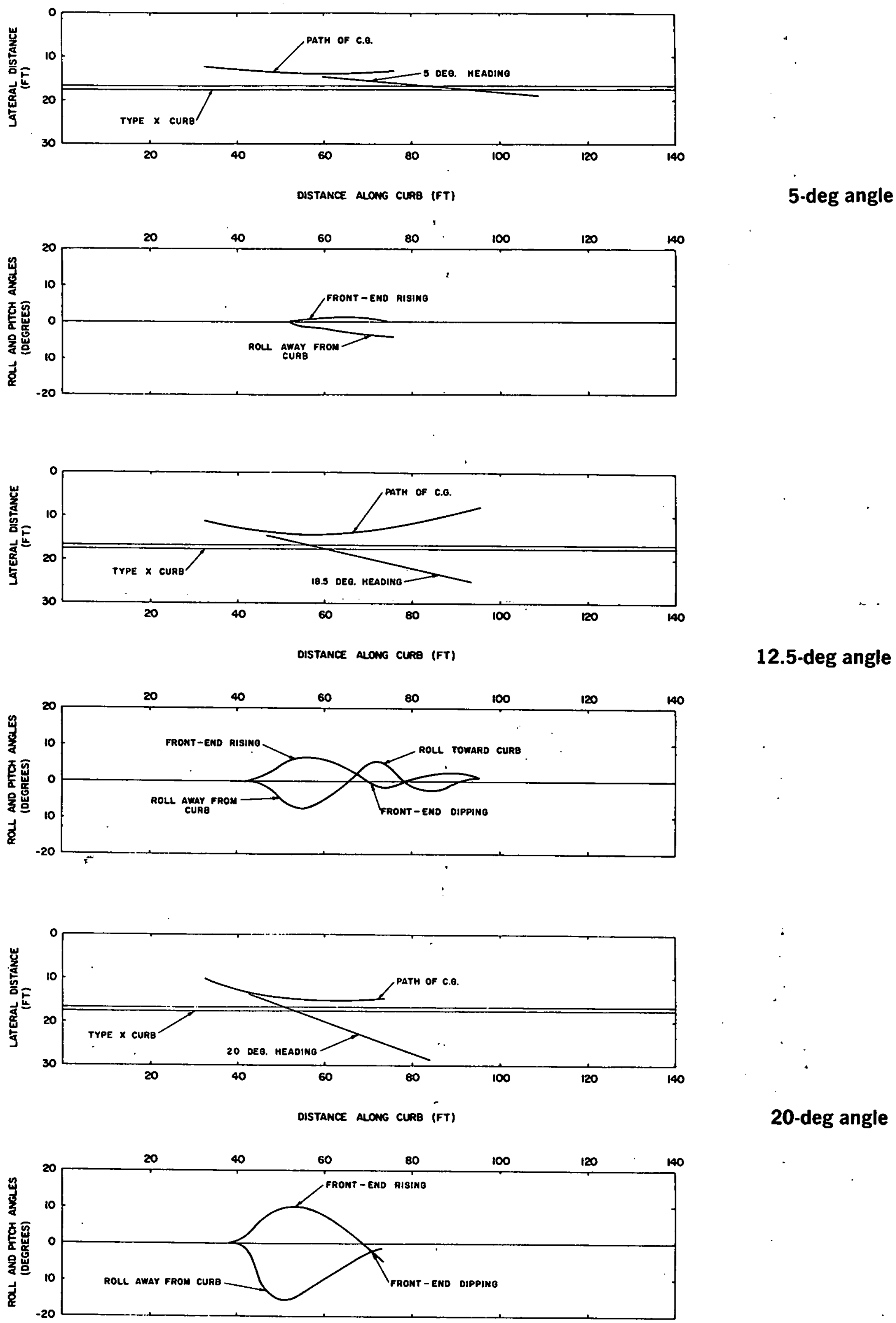


Figure E-16. Vehicle path, roll, and pitch for Type X curb with simulated impact of 30 mph.

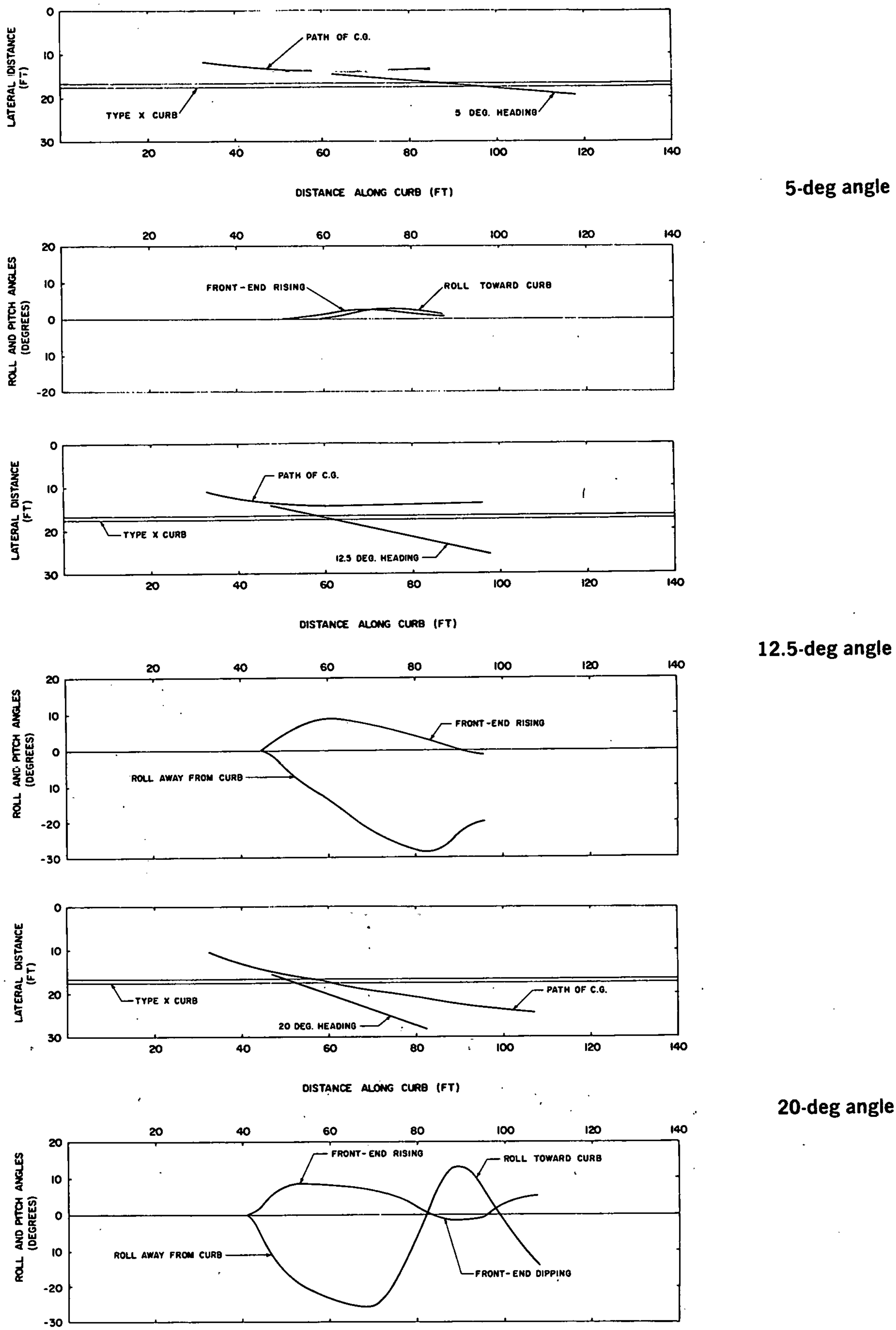


Figure E-17. Vehicle path, roll, and pitch for Type X curb with simulated impact of 45 mph.

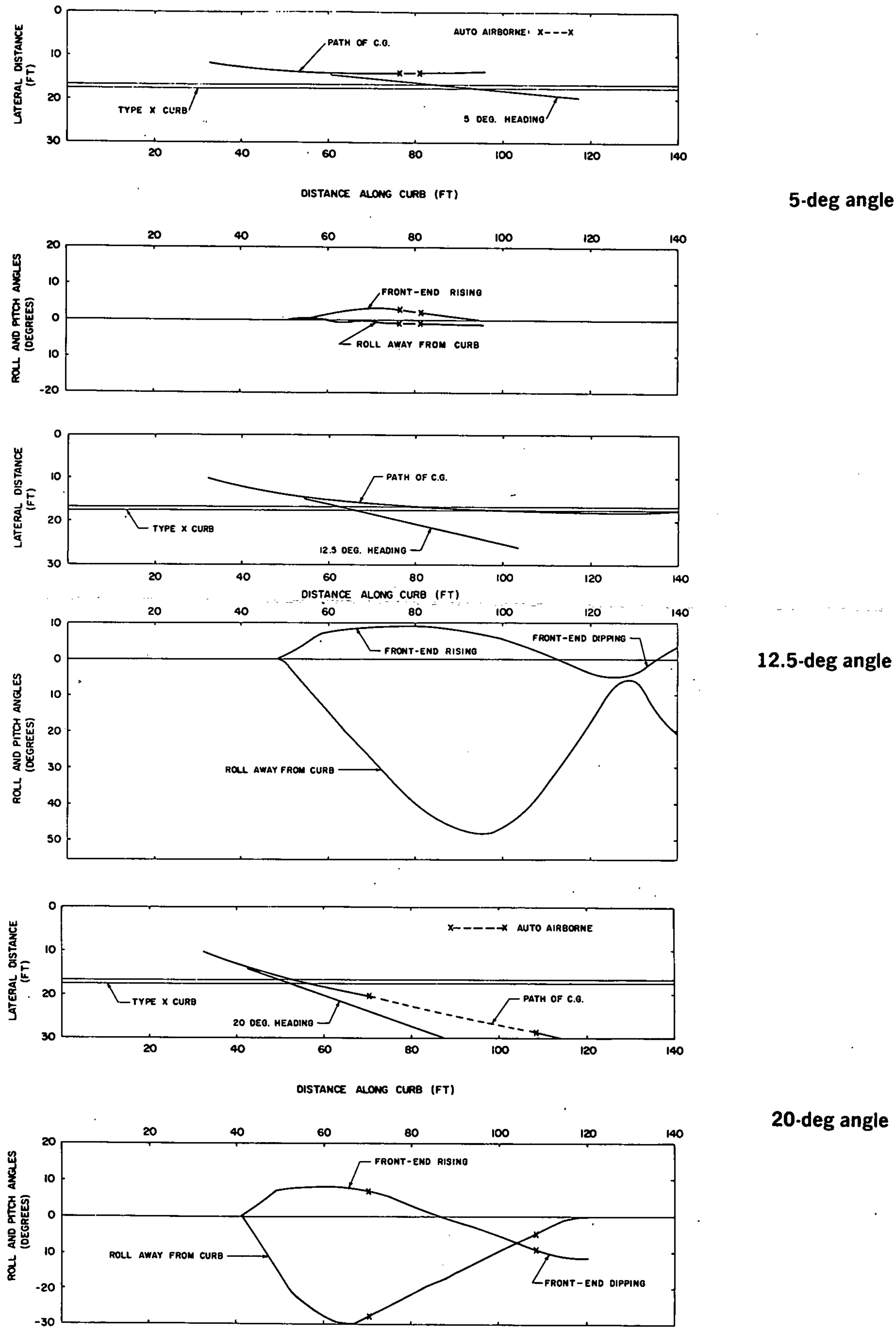
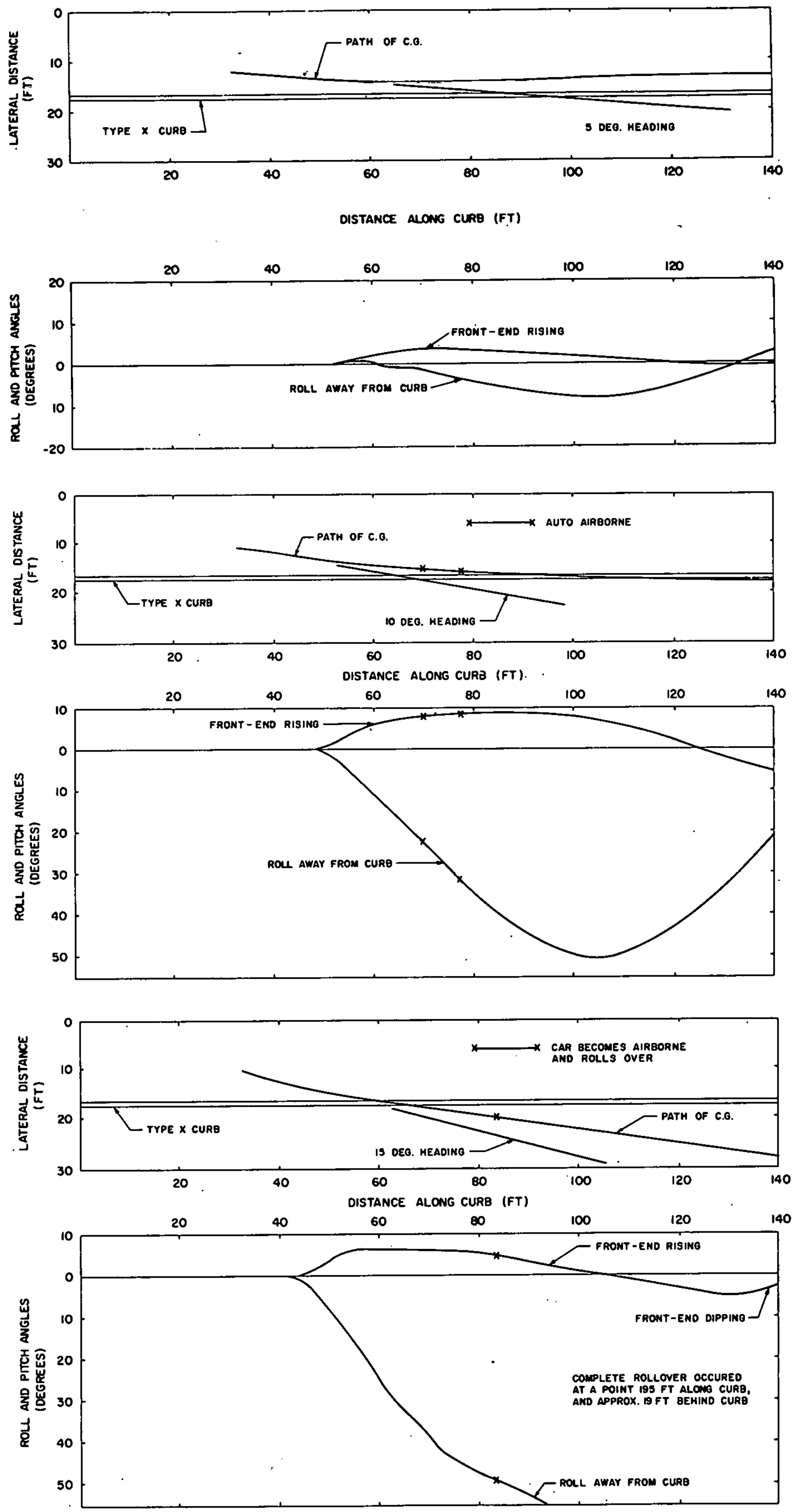


Figure E-18. Vehicle path, roll, and pitch for Type X curb with simulated impact of 60 mph.



5-deg angle

10-deg angle

15-deg angle

Figure E-19. Vehicle path, roll, and pitch for Type X curb with simulated impact of 75 mph.

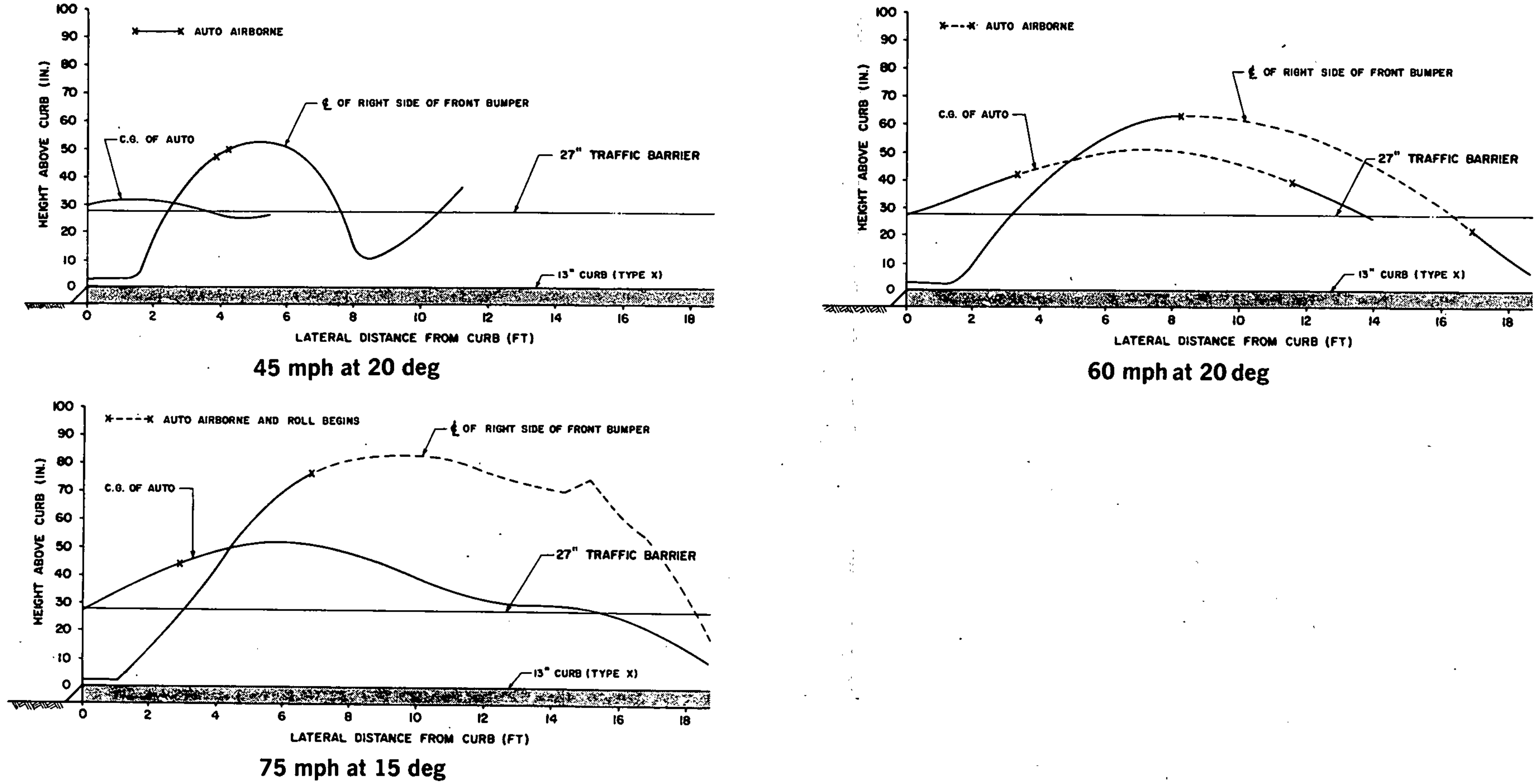


Figure E-20. Vertical rise of vehicle at various impact speeds and angles for Type X curb.

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* Highway Research Board Special Report 80.

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