Studies of Curb Impacts Using Highway-Vehicle-Object Simulation Model

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Studies of Curb Impacts Using the Highway-Vehicle-Object Simulation Model

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16. Abstract

The objective of the research study was to review previously conducted research efforts utilizing the Highway-Object-Simulation Model (HVOSM) for simulation of curb impacts and to reasses the validity of the HVOSM for this mode of operation. The effort involved review and assessment of data previously used to describe a specific vehicle, duplication of previously conducted simulation runs, measurement of certain vehicle parameters, evaluation of the sensitivity of vehicle responses to changes in vehicle parameters, and establishment of what is believed to be a "best" data set for describing the vehicle. Simulation runs were then made duplicating full-scale tests of the vehicle traversing curbs from which assessments of the validity of the HVOSM predicitions were made.

This research demonstrates that:

1. **The HVOSM provides an accurate prediction of the change in vehicle path due to changes in geometric elements.**

2. **When comparing HVOSM path predictions to full-scale test results, the dynamic properties of the vehicle used in the full-scale tests <u>must</u> be inputs for the simulated vehicle.**

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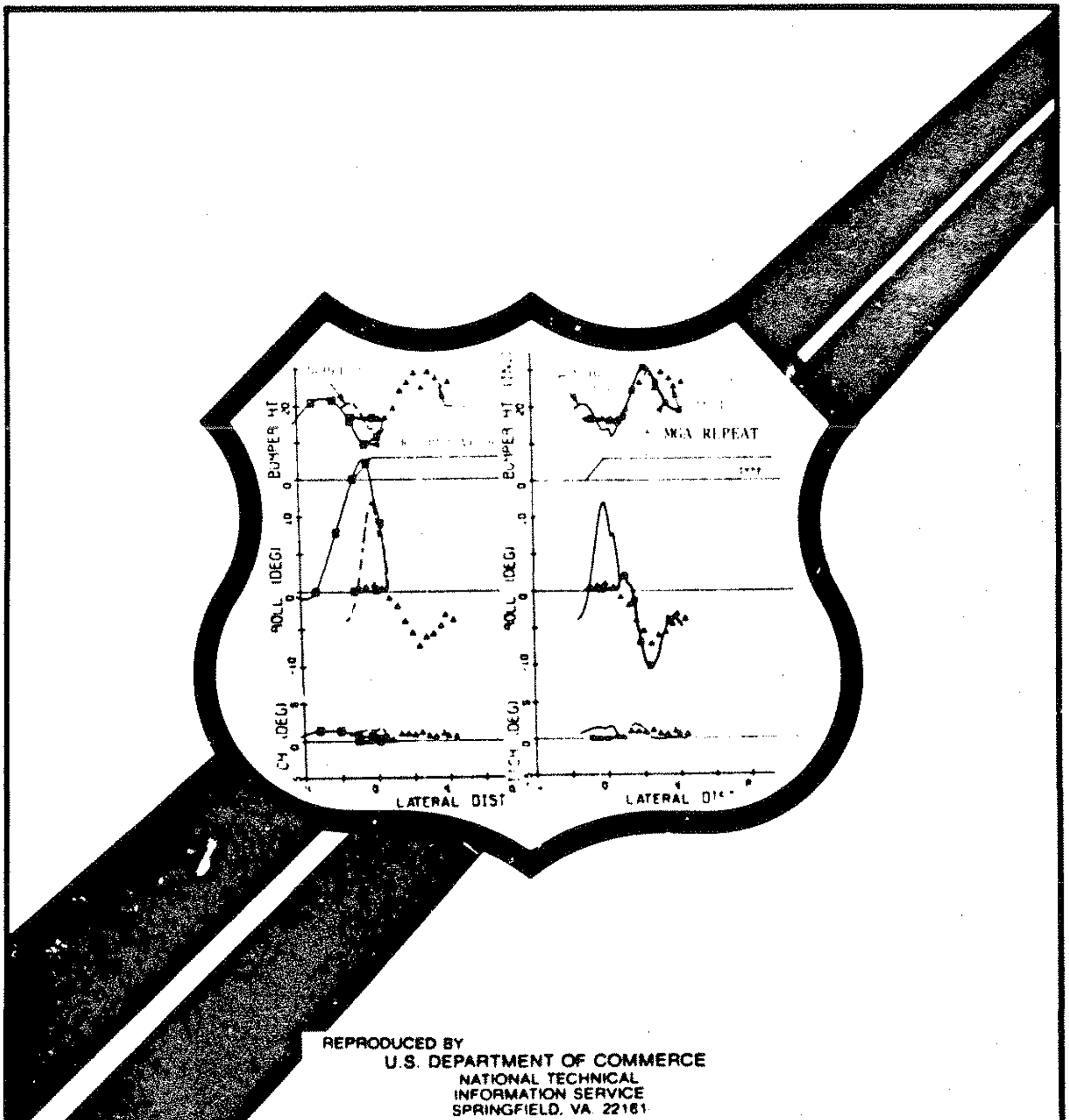
STUDIES OF CURB IMPACTS USING THE HIGHWAY-VEHICLE-OBJECT SIMULATION MODEL

U.S. Department of Transportation
Federal Highway Administration



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1. INTRODUCTION

In the mid-1960's, the Federal Highway Administration (FHWA) recognized the potential for digital computer based analytical tools to play an important role in studying and enhancing roadside safety design. Accordingly, a number of research projects were initiated to develop analytical models and computer simulations for that purpose. One such project was initiated at Cornell Aeronautical Laboratory (now Calspan Corporation) to develop a general, three-dimensional vehicle simulation which responded to control inputs and external disturbances in a realistic manner. The first stage of this development effort (Ref. 1) formed the structure of what was, through continued development efforts, to become known as the Highway-Vehicle-Object Simulation Model (HVOSM).

One feature of this early version of the HVOSM was the ability to simulate vehicle lateral and vertical responses when discontinuous objects, such as a curb, were encountered by the tires. A rather elaborate computer algorithm was developed to allow an approximation of tire enveloping power through representation of the tire as a series of equally spaced radial springs in the tire plane which individually produce forces as a result of their displacements caused by the terrain. Although comparisons with test results were made in order to establish that the simulated vehicle responded in a reasonable manner, no attempt at validation of the computer predictions for curb impacts was made due to the lack of accurate data for describing the test vehicles at that time.

Subsequently, a validation effort was undertaken (Ref. 2) to compare other modes of vehicle responses with test results. This effort included measurement of some properties of the vehicle used in the tests. A later effort, undertaken by the Texas Transportation Institute (TTI), for the National Cooperative Highway Research Program (NCHRP) was directed specifically toward a study of the HVOSM interactions with curbs and included modifications to the computer simulation, a validation effort encompassing full-scale curb tests with corresponding simulations, and a parameter study of vehicle impacts with curbs of various types and different encroachment conditions. This effort (Ref. 3) was published as NCHRP Report 150 (NCHRP 150) in 1974. More recently, a study (Ref. 4) was conducted by McHenry Consultants, Incorporated (MCI) under subcontract to Jack E. Leisch & Associates for the FHWA. This effort resulted in an unpublished FHWA report (FHWA report). This effort reviewed the analytical aspects of the TTI study and raised a number of issues with regard to the conclusions drawn.

The principal objective of this project was to review these two studies in order to resolve questions relative to the use of the HVOSM for curb impact simulations.

The questions to be addressed included:

- What data was used in the previous studies, was it appropriate and was it significant?
- Were differences in program versions significant in producing different vehicle responses in the studies?
- Is the HVOSM valid for predicting vehicle responses to curb impacts, and if so, with what qualifications?

The approach taken in this study included a thorough review of the results of these previous studies and of the data used to represent the vehicle within the HVOSM. This was then followed by duplication of runs previously made along with the conduct of a sensitivity study of selected parameters. Limited testing was also undertaken in an effort to measure certain vehicle properties which were felt to be significant in determining vehicular responses to curb impacts.

The remainder of this report is broken down into four major sections. Conclusions and recommendation are presented next. Documentation of simulation data is then provided. This is followed by discussions of the HVOSM sensitivity study and of the curb impact simulation results. Finally, a discussion of the overall results of the project is provided.

2. CONCLUSIONS AND RECOMMENDATIONS

Presented in this section are the conclusions and recommendation that have resulted from the study. The conclusions focus on three areas: 1) program versions used in previous studies, 2) data used in previous curb impact comparisons with test results, and 3) validity of the HVOSM in curb traversal situations.

2.1 Conclusions

1) Different versions of the HVOSM were used in the previous curb simulation studies conducted by TTI (Ref. 3) and MCI (Ref. 4). Based on a review of NCHRP 150, it is believed that the program versions were functionally equivalent in the treatment of suspension bump stop characteristics. It cannot be ascertained whether other program differences had an effect on predicted vehicle responses. However, it is clear that attempts at duplicating the NCHRP 150 run conditions resulted in different vehicle response predictions. These differences may have resulted from either program differences or data differences.

2) Differences in certain data items describing the vehicle had a strong influence on the predicted vehicle response differences observed between the two studies. Most significant of these are the steering system friction and tire bottoming location. The steering system friction value used in the FHWA research resulted in much better agreement with observed trajectories for type C curb traversals. Measurements of steering system hysteresis on the test vehicle at MGA indicate that the value used in the FHWA research was excessive. However, the improved agreement obtained with this excessive value is indicative of a deficiancy in some area of either vehicle data or modeling

representation of the steering system and/or the tire/curb interaction.

Differences in the tire deflection at which bottoming occurs is believed to be a major cause for angular response differences between the FHWA research runs and both the original NCHRP research runs and the runs conducted in this study, particularly for the type C curb cases. Neither an appropriate location for this bottoming, nor a representative value for bottoming stiffness are known and it is very likely that the simple bilinear tire rate representation is an inadequate description of tire performance at high deflections.

Sprung Mass inertia values used by in the NCHRP research in their validation study were inappropriate in that they represented the total vehicle inertia values. Inertia of the unsprung masses should have been subtracted in order to arrive at input values compatible with the HVOSM data requirements. While inappropriate values were used, they did not have a strong influence or vehicle responses.

3) Based on the results of this effort, it cannot be stated that the HVOSM is generally valid for simulating all curb impact situations. Results indicate that the program adequately simulated vehicular responses to type E curbs but did not reasonably simulate responses to traversing types C and X curbs. In the later cases, the simulated vehicle redirected much more readily than test vehicles. It is believed that modeling limtiations within the tire/curb interface are primarily responsible for this condition. However, additional full-scale testing and component testing would be necessary to better understand this interface and improve the model.

2.2 Recommendations

1) The current version of the HVOSM should not be used to simulate low-angle encroachment conditions with steeply faced curbs. Simulated responses to less steeply sloped curbs, such as the approximately 45-degree type E, appear generally in good agreement with test results. Thus, the use of the HVOSM for curbs of this nature or of a lesser slope is appropriate.

2) Testing should be undertaken to better understand the nature of the interaction between tires, curbs, and the vehicle steering system during curb traversals. Component testing should include measurement of tire curb interactions that produce vertical, lateral, and longitudinal forces acting on the tire and wheel at various attitudes and loading directions. Such tests would provide additional information for upgrading the tire model used in the HVOSM. In addition, additional full-scale tests should be undertaken to measure steering system responses to curb traversals. These tests would provide information for upgrading the HVOSM steering system representation, but would also develop more detailed information for comparison with simulated vehicle responses.

3) Based on the results of the recommended testing, modifications to the HVOSM should be undertaken to more accurately represent the curb traversal event. Changes should include modifications to the current thin-disk tire representation to include direct development of lateral tire forces as a result of lateral deformation and longitudinal tire forces due to scrubbing.

3. DOCUMENTATION OF SIMULATION DATA

The intent of this section is to document data used, sources of those data that have been used to represent a specific vehicle, and the implications of that data on vehicle responses in related curb traversal simulation studies. As has been indicated, the NCHRP 150 gave findings from full-scale vehicle curb traversal tests, simulation of those tests with the HVOSM for validation purposes, and a simulation parameter study of vehicle behavior to various curbs at a range of encroachment conditions (Ref. 3). A related research study undertaken for FHWA was an effort to improve the correlation between simulation and test results observed in the previous study. This effort was documented in a draft report of June 1982 (Ref. 4).

The following subsection presents and discusses the data utilized in each of these studies to represent the vehicle in a mathematical sense as required by the HVOSM. Sources of data are indicated where traceable. In order to establish a firm foundation for the remainder of the effort, computer simulation runs from both previous research studies were duplicated. Results from these runs are then discussed. Following this, results of a parameter sensitivity study are summarized. The intent of this series of computer runs was to identify those vehicle parameters which had a strong influence on vehicle responses to curb traversals and thus must be specified accurately for valid simulation results. Finally, the establishment of a "best" available data set for simulation of the curb traversal tests documented in NCHRP 150 is described.

3.1 Documentation of Data Used in Previous Studies

Presented in this section is documentation of vehicle data used in two previous simulation studies of curb impacts. It is noted that the more recent FHWA study contained a complete documentation of all data used in the simulation study. The NCHRP study contained documentation of most vehicular data used; however, some data required by the program was not explicitly identified. As a result, the data listings discussed below contain some unknown values and some information which is believed to be that used NCHRP study but that cannot be confirmed.

Table 1 presents a comparison of inertial and dimensional inputs to the HVSOM used in the two previous studies to the extent that documentation is available in the respective reports. Note that the two sets of inputs were used in the NCHRP study. The first was intended to represent the full-scale test vehicle and therefore was used in the validation comparisons. The second was intended to represent a more typical full-size vehicle of the period. Note that the test vehicle was of special design for police work including a heavy-duty suspension and was modified further for the protection of the driver and installation of data acquisition equipment on the test program. This second vehicle data set was then used after validation in a parameter study of various encroachment conditions and curb combinations.

For purposes of evaluating vaildity of the HVOSM in curb impact situations, it is only that data that reflects the test vehicle which is important. Hence, the subsequent discussion will relate only to data sets which where intended to represent that vehicle.

As seen in table 1, the unsprung mass values differ only slightly. The values used in the FHWA study were derived from measurements as reported in Ref. 2; whereas, the values used in the NCHRP study were derived from regressions to typical data (Ref. 5). Principal moments of inertia are, however, quite different. The values used in the FHWA study are derived from the average of two estimates: a) adjusting mass while assuming identical radius of gyration from those reported in Ref. 2 and b) regression to vehicle weight as described in Rasmussen in Ref. 5. The values for pitch and yaw inertia in NCHRP 150 were also developed from equations given in Ref. 5 but are erroneous in that they apply to the total vehicle. Inertia contributions of the unsprung masses should be removed so that sprung mass values are supplied to the HVOSM. A difference is also apparent in the rear axle roll

Table 1

INERTIAL AND DIMENSIONAL DATA

Variable	Units	FHWA Study (Ref. 4)	NHCRF Study (Ref. 3) Validation Data
M_S	lb s^2/in	9.317	9.318[3]
M_{UF}	lb s2/in	0.608	0.590[1]
M_{UR}	lb s^2/in	0.945	0.9612
I_X	lb s2-in	50283	50284
I_Y	lb s^{2}-in	28678	32712[4]
I_Z	lb s2-in	33029	42504[4]
I_{XZ}	lb s^{2}-in	-192	-192 6
I_R	lb s2-in	435.66	600[6]
a	in	54.55	54.55[8]
b	in	64.45	64.45[3]
T_F	in	61.2	61.0[9]
TR	in	60.5	60.0[9]
	in	-2.0	-2.09
TS	in	46.52	46.5
Sprung Mass CG Height	in	24.14	24.138

1 Unsprung mass values from Ref. 2
2 Calculated from Rassmussen regression (Ref. 5)
3 Calculated by average of computed Rasmussen values and constant radi of gyration values from Ref. 3 data
4 Computed from Rassmussen relationships. Note I_Y, I_Z, are for total vehicle
5 Source unknown
6 "Best Estimated" Value from Ref. 2
7 Value used in Ref. 2 validation comparisons
8 Inferred from Figure B-2 Ref. 3
9 Value used in the NCHRP parameter study. Also believed to be used in validation effort.

1 lb-s^2/in = 17.86 kg·s^2/m
1 lb-s^2-in = 0.113 N·s^2· m
1 in = 25.4 mm

moment of inertia with the smaller value based on a measurement and the larger based on an estimate, both of which were published in Ref. 2. Thus, rather substantial differences exist in moments of inertia of the sprung mass in pitch and yaw and of the rear axle in roll between the data used in the two previous studies.

Also shown in table 1 are dimensional data used by the HVOSM. Note that the longitudinal location of the sprung mass center of gravity, as defined by the variables a and b, are the same in both studies. The same is true for the sprung mass c.g., height. The use of these dimensions in the NCHRP study were inferred from Figure B-2 in Ref. 1. Other dimensional information was not located in Ref. 1 and was solicited from personnel participating in the NCHRP study. Copies of a parameter study computer printout were supplied by which contained the dimensional data indicated for T_F, TR, and in the table. It is assumed that the same values were used in the validation study.

Table 2 summarizes front and rear wheel rate and bump stop data. Note that according to the input data listings in Ref. 3, the version of the HVOSM used in the NCHRP study did incorporate an upgrade in the bump stop algorithm documented in Ref. 6. This upgrade included nonlinear, energy dissipating bump stops located at different positions in jounce and rebound from equilibrium. The form of one nonlinear term is different from that of the program version used in the FHWA study, but the bump stop characteristics produced are the same. Consequently, no differences in vehicle responses can be attributed to these suspension properties.

Table 3 lists additional suspension properties and steering system characteristics used in the studies. As is seen, the FHWA study used considerably smaller viscous damping coefficients for the front and rear than were used in the NCHRP study. Friction values were essentially the same at the front but quite different at the rear. Both sets of damping coefficients

Table 2

SUSPENSION RATE DATA

Variable	Units	FHWA Study (Ref. 4)	NCHRP Study (Ref. 3) Validation Data
K_F	lb/in	131	131
KFC	lb/in	300	300
K'_{FC}	lb/in^3	600	600[1]
KFE	lb/in	300	300
K'_{FE}	lb/in^3	600	600[1]
F	-	0.5	0.5
FC	in	-3.0	-3
FE	in	5.0	5
K_R	lb/in	194	192
KRC	lb/in	300	300
K'_{RC}	lb/in^3	600	600
KRE	lb/in	300	300
K'_{RE}	lb/in^3	600	600
R	-	0.5	0.5
RC	in	-4.0	-4
RE	in	4.5	4.5

[1] Expressed in HVOSM-RD2 equivalent values.

1 lb/in = 17.86 kg/m
1 lb/in^3 = 27680 kg/m^3
1 in = 25.4 mm

Table 3
SUSPENSION AND STEERING DATA

Variable	Units	FHWA Study (Ref. 4)	NCHRP Study (Ref. 3) Validation Data
C_F	(lb-sec/in)	1.3	3.5
CF'	(lb)	58	55
F	(in/sec)	.001	.001
CE	(lb-sec/in)	1.75	3.9
C_R'	(lb)	97	50
R	(in/sec)	.001	.001
R_F	(lb-in/rad)	266000	266000
RR	(lb-in/rad)	59244	61900
K_{RS}		.059	0.07
I	(lb-[illegible]-in)	300	492.0*
C'	(lb-in)	5000	600.*
	(rad)	.523	0.4*
K	(lb-in/rad)	1000000	5000*
E	(rad/sec)	.05	0.075*
P	(in)	1.5	1.5*

*Values used in parameter study presumed to be used in validation runs.

1 lb·in = 0.133 N·m
1 lb-s/in = 17.86 kg·s/in
1 lb = 0.454 kg
1 in/sec = 25.4 mm/s
1 lb-in/rad = 0.133 N·m/r

were reported in Ref. 2, the larger being estimated and the smaller values reflecting measurements.

Steering system parameters used in the NCHRP validation study were not explicitly reported. However, values used in their parameter study were confirmed and are assumed to be the same as those used in the validation runs.

Tire parameters are shown in table 4. The NCHRP report did not document the deflection-developing increment (DRWHJ) and maximum deflection of the tire (RWHJE) used for developing radial spring characteristics for use in the curb impact mode, nor the undeflected radius of the tires. Other tire parameters are the same with one exception. That is, the value of T used in the FHWA study was 6 inches (152.4 mm) while thar used in NCHRP report was 3 inches (76.2 mm). This parameter reflects the tire deflection at which bottoming occurs and, thus, can have a substantial difference in tire radial forces produced.

Other data indicated in table 5 was reported in the FHWA study but not in the NCHRP study. Sources of data, where known, are indicated.

3.2 Duplication of Previous Curb Computer Simulations

The purpose for duplicating the runs of the previous studies was to attempt to verify input data that were used and to establish a firm basis from which comparisons could be made. Originally, the plan of the FHWA study simulations was to duplicate selected runs as a means of spot checking the NCHRP results. The printouts documenting the FHWA simulations and the printouts from MGA's duplications were compared and the agreement was found to be very good. Generally, the differences between corresponding runs were less that 1 percent. Results of the post-processing program were also compared and found to be in good agreement with FHWA study results for which MGA had hard copy outputs. However, in some instances, the post-processing data that was plotted at MGA did not agree with the data plots contained in the FHWA report

Table 4
TIRE DATA

Variable	Units	FHWA Study (Ref. 4)	NCHRP Study (Ref. 3) Validation Data
RWHJE	(in)	8.0	?
DRWHJ	(in)	.25	?
K_T	(lb/in)	1300	1300
T	(in)	6	3
T		10	10
A0		4000	4000
A_1		8.4	8.4
A2		3000	3000
A_3		1.71	1.71
A4		4200	4200
T		1.0	1.0
		0.8	0.8
RW	(in)	14.68	14.68*

*Assumed

1 in = 25.4 mm
1 lb/in = 17.86 kg/m

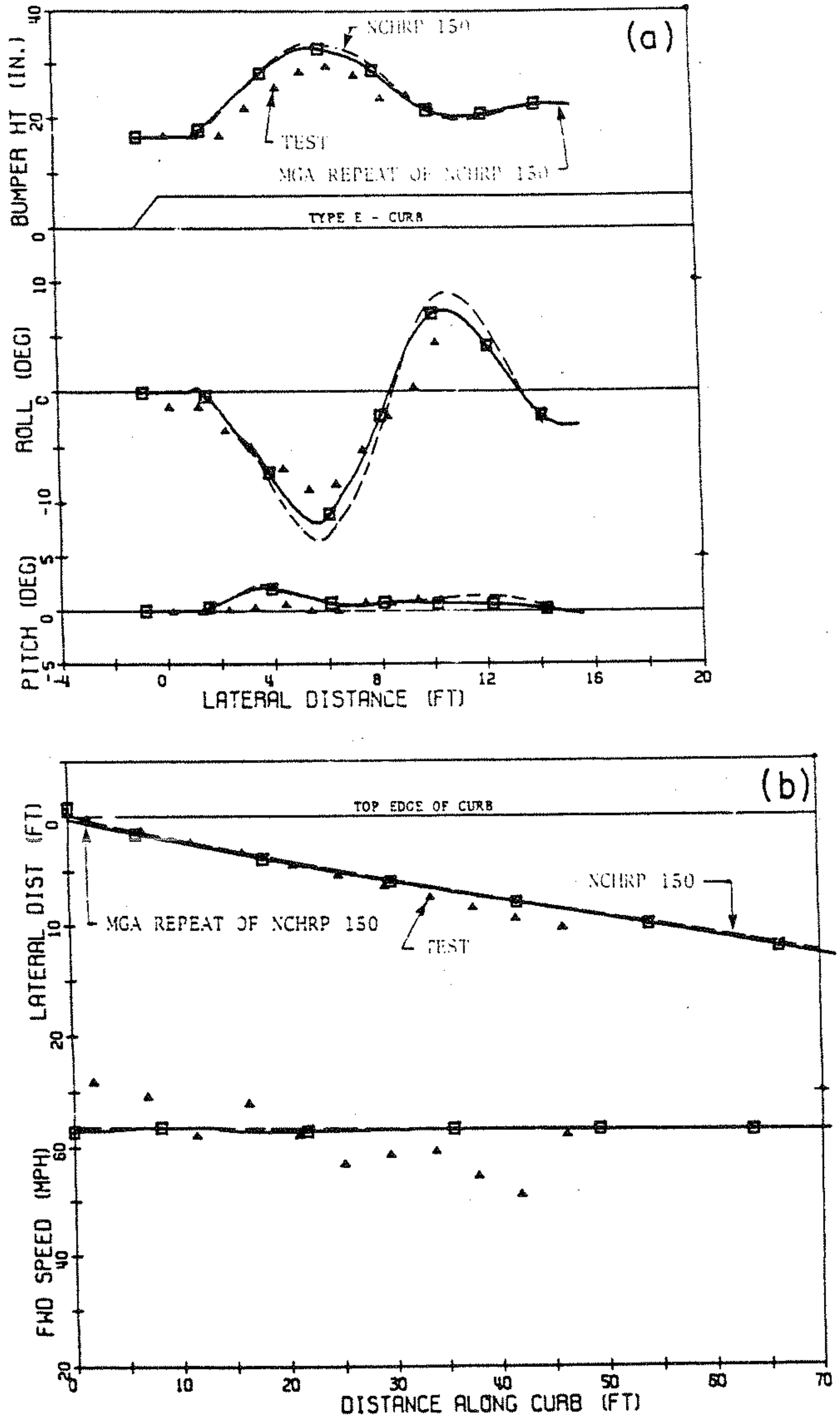
Table 5

OTHER HVOSM DATA

Variable	FHWA Study (Ref. 4)	NCHRP Study (Ref. 3) Validation Data
Camber Data	Ref. 2	unknown
Track change data	unknown	not applicable
Antipitch data	Ref. 7	unknown
Control tables	drag force	unknown

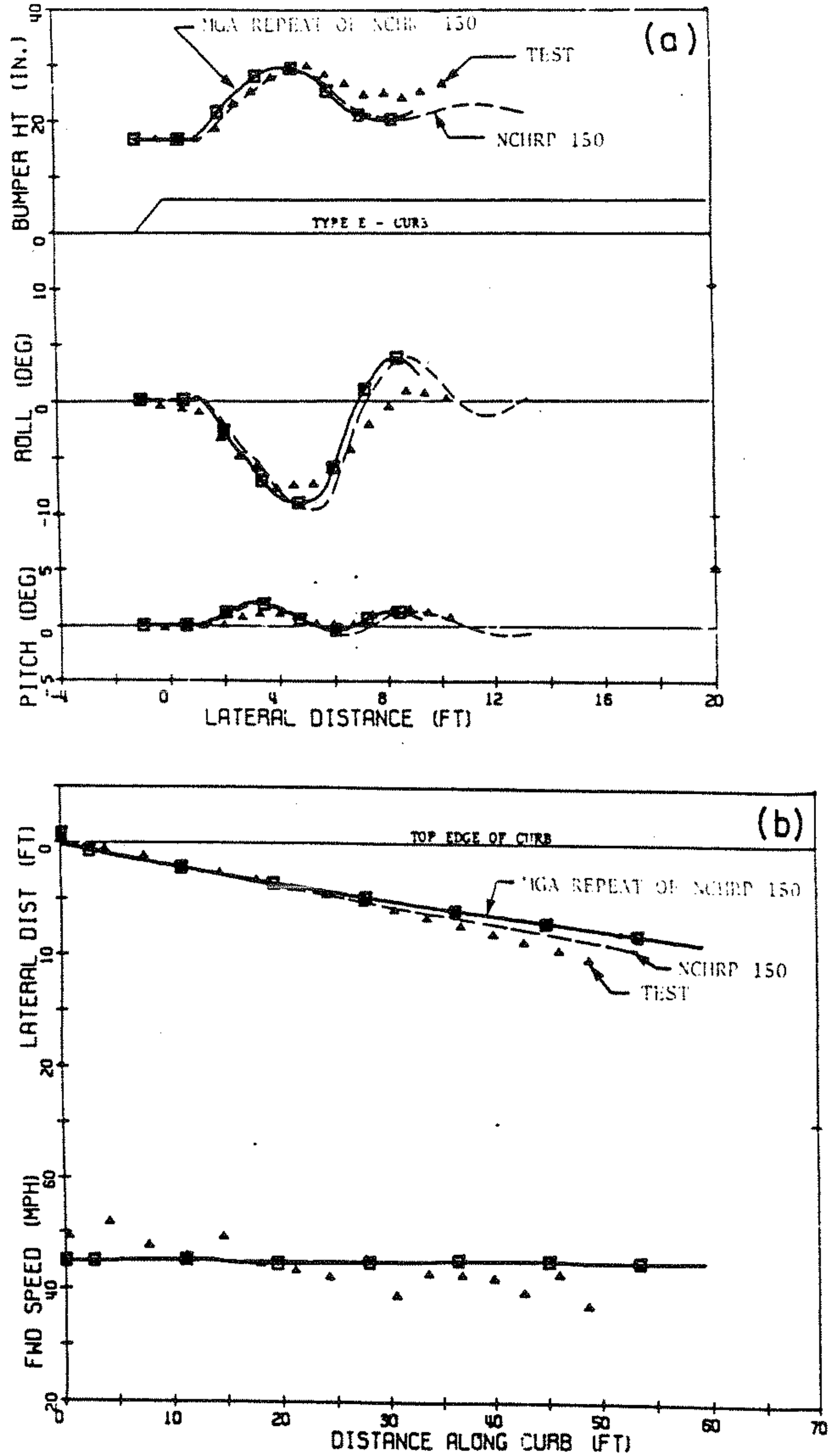
(Ref. 4). In an attempt to discover the reason for this, FHWA personnel participating in the FHWA study were contacted. During these discussions, it was learned that the results were hand plotted thus, somewhat susceptable to manual errors. As a result, it was felt that complete duplication of all runs was necessary to eliminate any possibility of erroneous plots influencing subsequent data comparisons.

The checking of the NCHRP study results was not as simple a matter. Direct duplication of the NCHRP study runs was not possible since certain inputs could not be confirmed. In light of this, all NCHRP study runs were "duplicated" using judgment in supplying the input data which were unknown or uncertain. These "duplications" did produce results different from those obtained in the simulations made in the NCHRP study. In general, the runs made by MGA give the same response behavior patterns as those made in the NCHRP report. The differences manifest themselves in the form of either a disagreement in the ranges of bumper height, roll, and pitch or a disagreement in trajectory. Figure 1 shows the results of the duplication of run N-7. This is a good example of the trajectory being in good agreement but the range of values for bumper height, roll, and pitch not being in agreement. For this case, the duplicated vehicle did not respond to as great a degree as the vehicle defined in the NCHRP simulations and generally compares more favorably with the corresponding results. Figure 2, which shows the results of the duplication of run N-6 (medium speed, medium impact angle), is an example where the ranges of bumper height and pitch and roll angle responses are in agreement but the trajectory varies. A clear example of all the vehicle responses not being in agreement with the NCHRP results is given in figure 3. This figure shows the comparison between the MGA duplication and NCHRP test N-17 (high speed, low impact angle). In this case, both simulation results predict redirection which was not observed on the test. This duplicated run shows a considerably larger roll response than does the original NCHRP run. The results obtained from duplicating all 18 NCHRP runs can be found in appendix A. In general, for all the duplication runs which involved the type E curb, the main area of disagreement with the original NCHRP runs involved



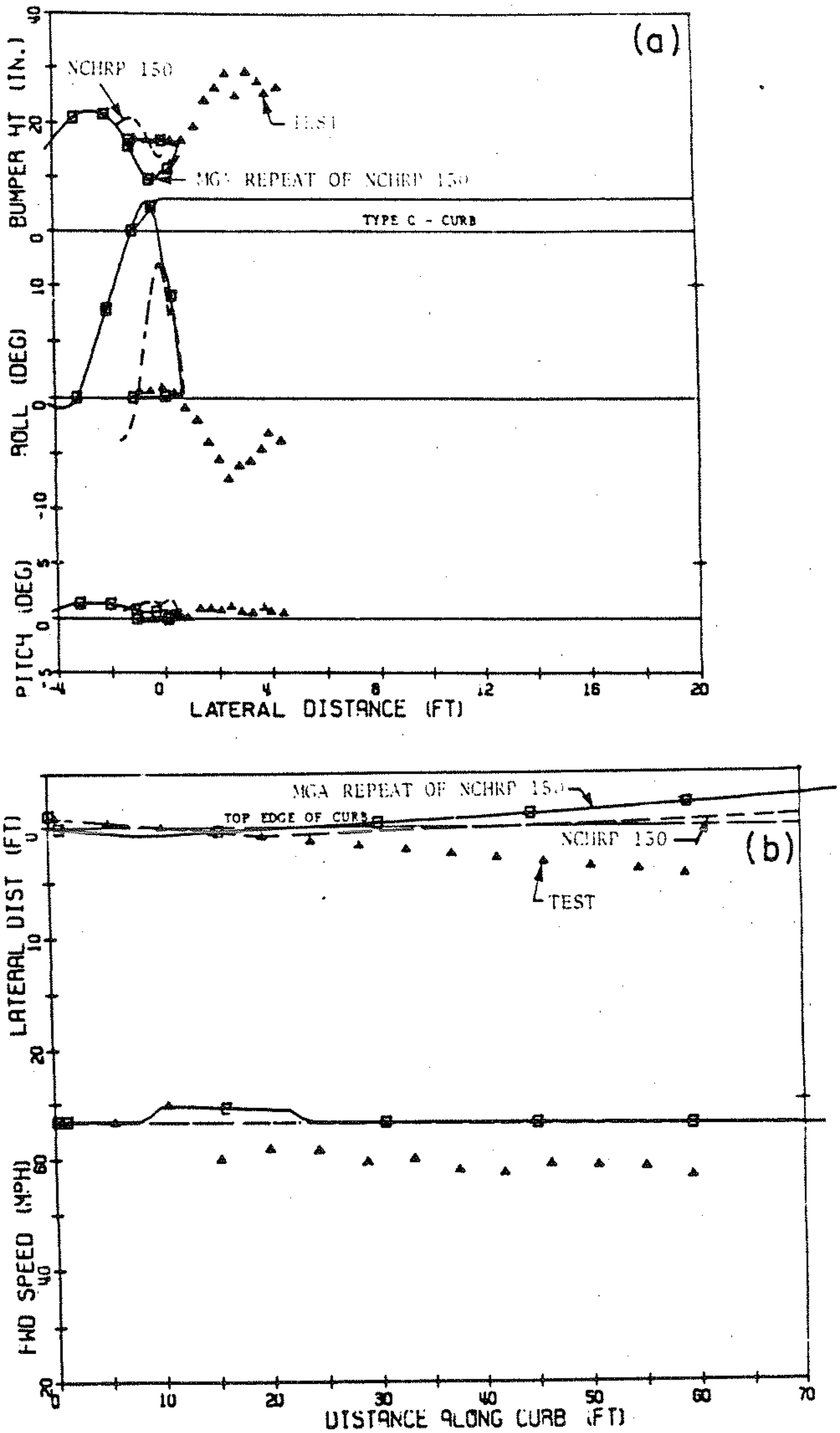
*1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 1 DUPLICATION OF TTI RUN N-7. CURB TYPE E. 60 MPH & 12.5 DEGREE IMPACT: (A) VEHICLE ROLL, PITCH, & BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH.



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 2 DUPLICATION OF TTI RUN N-6. CURB TYPE E. 45 MPH & 12.5 DEGREE IMPACT: (A) VEHICLE ROLL, PITCH, & BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH.



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 3 DUPLICATION OF TTI RUN N-17. CURB TYPE C. 60 MPH & 5 DEGREE IMPACT: (A) VEHICLE ROLL, PITCH, & BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH.

differences in trajectory, while the type C curb run duplications involved the differences in bumper height, roll, and pitch ranges and trajectory.

Although the results from the MGA duplications did not match those from the original runs, they were deemed sufficient to represent those original runs due to their agreement on general response behavior patterns. With the two sets of data available, a basis for comparison was established. Comparison to the full scale tests conducted for NCHRP on the basis of actual numerical data is limited. The only such data found in the NCHRP 150 report which deals with the validation study is shown in table 6. This table provides information on the curb impact conditions (schedule* and actual) and the maximum of bumper rise (height) above the curb and vertical accelerations of the sprung mass. As a means of comparison, tables 7 and 8 have been prepared. Comparisons of corresponding data on these three tables indicated that in general, the "duplicated" NCHRP runs give responses closer to the full scale tests for the type E curb impacts, while the duplications of the FHWA runs come closer to the test results for the typc C curb impacts.

Tables 7 and 8 also include additional information. This additional information (max. roll, max. pitch, bumper height at 2 feet (0.6m) offset and lateral distance to max. rise input) has been included since it was tabulated from the FHWA run results. These tables immediately show how the differences in input data affect the results.

For ease of comparison, the graphical results of the FHWA duplications have been included in appendix B. From a quick overview it is seen that both sets of results generally agree concerning trajectory (whether and/or how much the simulated vehicle redirects). There are, however, three exceptions. These included the runs N-2 (low speed, low-angle impact), N-15 (low speed, high-angle impact), and N-17 (high speed, low-anlge impact). Runs N-15 and N-17 involve the type C curb and illustrate that the FHWA study defined vehicle did redirect. (figures 3-4 and 3-5) The opposite is true for N-2 which involves the type e curb. (Figure 6) The graphical results also

Table 6

SUMMARY OF FULL-SCALE TEST 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.)	[d] 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 viscorder traces.

Source: See Reference 3

Multiply in by 25.4 to obtain mm
Multiply mph by 1.609 km/h

Table 7

SUMMARY OF RESULTS FROM DUPLICATIONS OF THE NCHRP AND FHWA RUNS FOR CURB TYPE E

Test	Approach Speed (mph)	Approach Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. Peak Vertical Acc. (G)	Bumper Hgt. above curb 2 ft. offset (in)	Max. Bumper Hgt. above curb (in)	Lat. Dist. to Max. rise point (ft)
MGA Duplication of								
NCHRP Run N-2	30.4	5.1	-7.75	1.91	-0.23	16.6	21.7	1.2
N-3	45.6	5.0	-9.45	1.66	-0.58	23.3	23.3	2.0
N-4	59.3	4.6	-10.00	1.43	-0.80	22.6	24.0	2.4
N-5	32.0	11.6	-7.33	2.40	-1.10	17.1	22.1	3.4
N-6	45.3	11.1	-9.14	2.12	-1.71	15.7	23.8	4.3
N-7	63.6	12.6	-11.89	2.17	-4.53	13.9	27.3	5.6
N-8	32.7	18.5	-6.59	2.76	-3.13	13.4	22.5	5.0
N-9	41.8	18.7	-8.13	2.79	-2.46	12.8	24.5	5.7
N-10	63.0	17.6	10.61	2.54	-4.99	12.2	28.7	8.4
MGA Duplication of								
FHWA Run N-2	30.4	5.1	-3.08	-1.00	0.37	N/A	15.1	0.29
N-3	45.6	5.0	-9.58	1.39	-0.92	17.4	23.1	1.5
N-4	59.3	4.6	-10.11	1.10	-0.78	29.3	29.6	2.1
N-5	32.0	11.6	-7.91	2.69	-1.98	18.0	22.5	3.1
N-6	45.3	11.1	-9.57	2.08	-2.60	21.0	30.0	4.2
N-7	63.6	12.6	-10.74	1.72	-3.03	12.0	24.9	6.5
N-8	32.7	18.5	-7.72	2.55	-2.89	12.1	23.0	5.3
N-9	41.8	18.7	-8.38	2.34	-2.03	17.6	29.7	6.2
N-10	63.0	17.6	8.88	2.28	-2.37	11.0	26.2	9.1

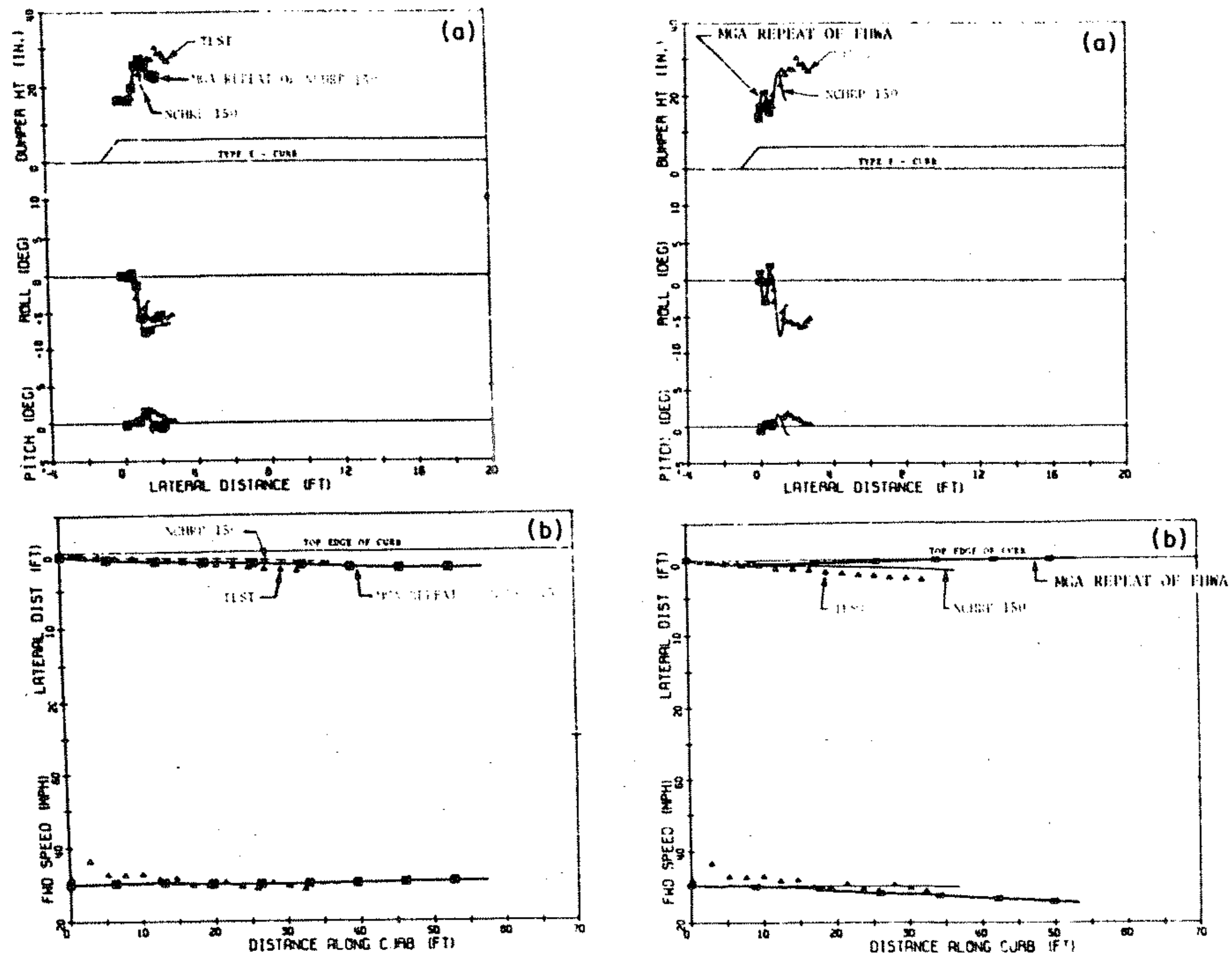
Multiply ft by 0.305 to obtain m
Multiply in by 25.4 to obtain mm
Multiply mph by 1.609 to obtain km/h

Table 8

SUMMARY OF RESULTS FROM DUPLICATIONS FOR CURB TYPE C

Test	Approach Speed (mph)	Approach Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. Peak Vertical Acc. (G)	Bumper Hgt. above curb 2 ft. offset (in)	Max. Bumper Hgt. above curb (in)	Lat. Dist. to Max. rise point (ft)
MGA Duplication of								
NCHRP Run N-11	34.2	4.9	7.09	-1.23	-2.56	N/A	11.4	0.0
N-12	44.7	5.1	9.00	-0.58	-1.22	N/A	11.6	0.0
N-13	34.2	11.2	-4.12	2.87	-1.70	19.2	20.7	2.5
N-14	43.5	12.8	-6.99	2.72	-3.94	15.3	24.3	6.2
N-15	32.1	17.4	-8.13	2.83	-3.26	14.1	21.9	3.7
N-16	43.0	18.4	12.05	2.92	-7.91	13.7	25.8	5.8
N-17	66.5	5.1	17.79	1.49	-1.19	N/A	11.6	0.0
N-18	62.2	12.3	13.00	2.58	-7.56	14.5	29.1	5.3
N-19	61.5	18.6	19.38	2.94	-9.27	12.5	28.2	8.7
MGA Duplication of								
FHWA Run N-11	34.2	4.9	5.57	1.43	-2.20	N/A	14.0	.30
N-12	44.7	5.1	7.53	-1.17	-1.26	N/A	14.7	.01
N-13	34.2	11.2	-5.85	2.59	-3.19	19.1	21.4	2.6
N-14	43.5	12.8	-6.51	2.14	-3.84	13.5	23.5	4.8
N-15	32.1	17.4	-6.60	2.40	-3.47	12.6	22.4	5.0
N-16	43.0	18.4	-7.95	2.07	-2.18	11.9	23.5	6.6
N-17	66.5	5.1	-10.57	1.64	-1.69	24.2	25.7	2.3
N-18	62.2	12.3	10.04	1.65	-2.70	17.3	29.8	5.9
N-19	61.5	18.6	8.68	2.30	-4.62	11.3	25.9	9.6

Multiply ft by 0.305 to obtain m
Multiply in by 25.4 to obtain mm
Multiply mph by 1.609 to obtain km/h



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure [illegible] EXCEPTION NO. 1 IN VEHICLE TRAJECTORY AGREEMENT

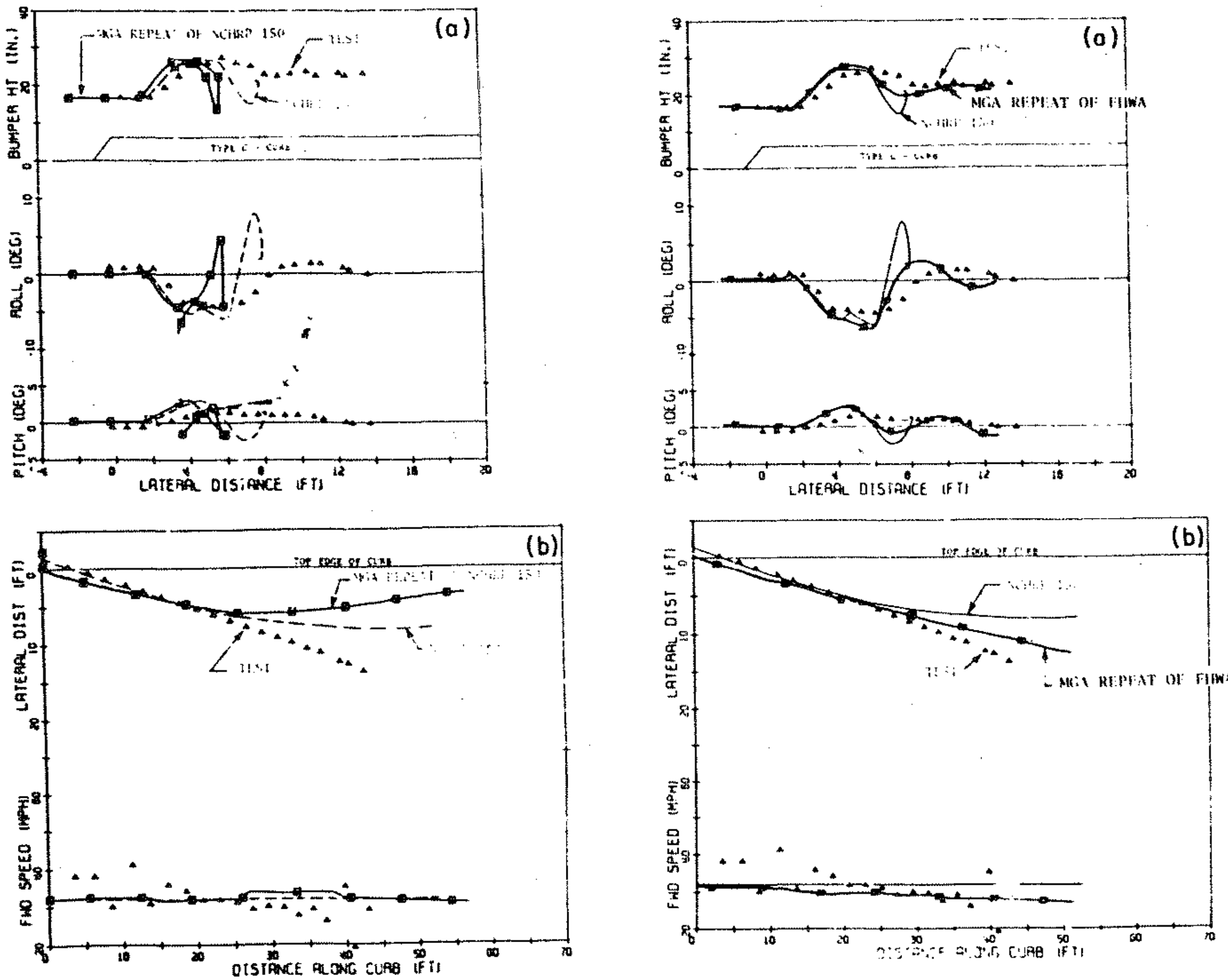


Figure 5 EXCEPTION NO. 2 IN VEHICLE TRAJECTORY AGREEMENT

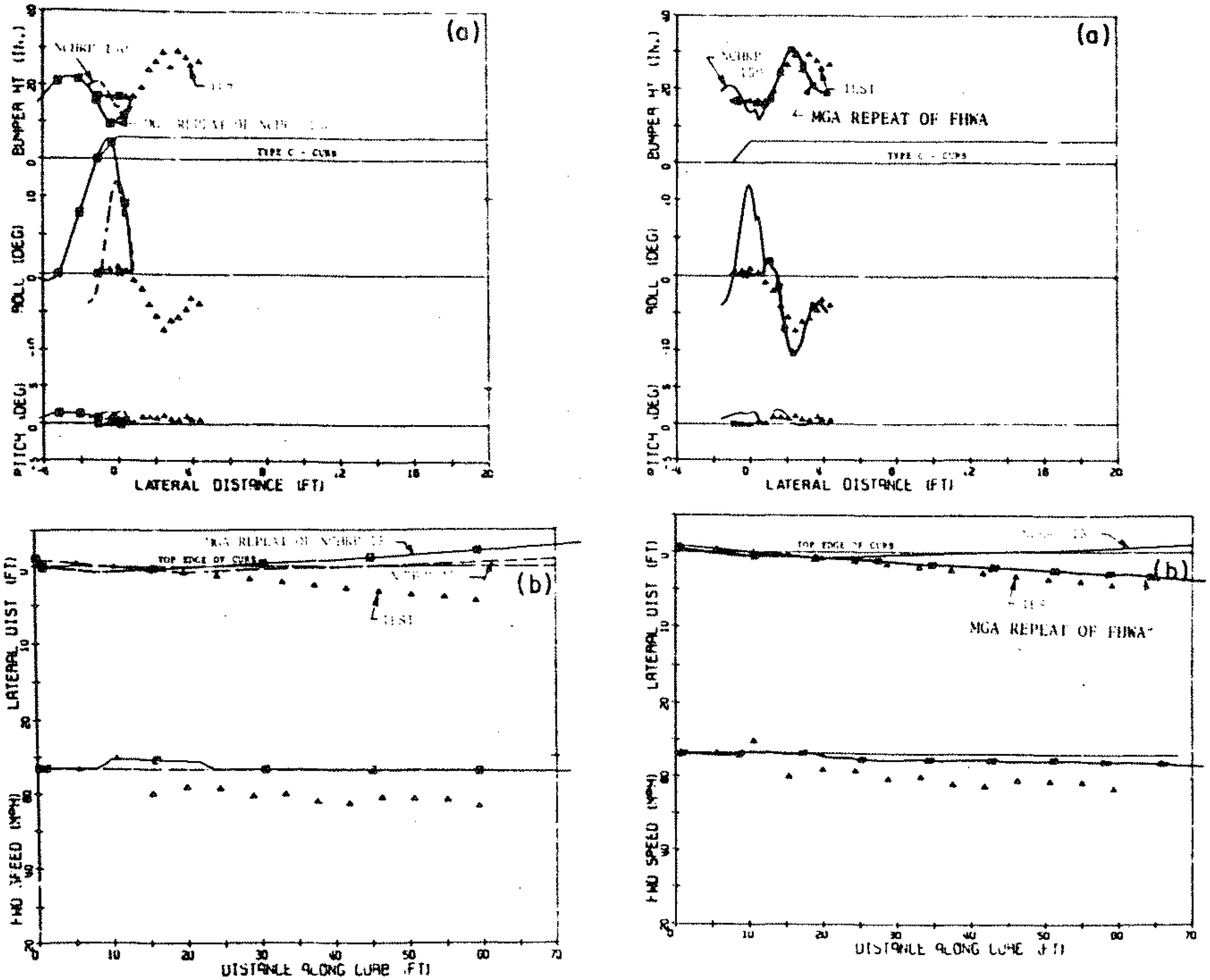
1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

support table 7 and 8 in showing that there are differences in the ranges of responses for all runs. In general, as the encroachment speed increases the differences become more apparent. This is also true for increasing encroachment angle for the type C curb. (figure 7) Also, the FHWA responses are closer to the test results for the Type C curbs and the high angle impacts for the type E curbs while the NCHRP predictions are closer to the test results for the low-angle impacts for the type E curb.

3.3 Effects of Variations of HVOSM Parameters on Vehicle Reponses to Curb Impacts

Comparisons the previous studies results for the curb impact simulations have shown that input differences certainly affect the results. To determine to what degree input differences are important, MGA conducted a sensitivity study on parameters deemed as likely to be the causes for the response differences. The input parameters varied were suspension damping, tire bottoming deflection, sprung mass pitch inertia, sprung mass yaw inertia, steering system interia, steering system friction, rear axle roll interia, and suspension system friction. Table 9 shows the baseline values and the variations used for each parameter. It should be noted that the baseline data is from the FHWA definition of the test vehicle. This data set was used in order to confirm whether the changes made by FHWA to the input deck were a significant factor in the different responses from the orignial NCHRP validation runs. The run conditions chosen for the sensitivity study are those found in runs N-2, N-10, N-15, and N-17. These four were chosen because they represent the extremes of the encroachment conditions, namely, low speed/low angle (run N-2), high speed/high angle (run N-10), low speed/high angle (run N-15), and high speed/low angle (run N-17).

Table 10 summarized the results of the sensitivity study by giving the maximum roll and pitch angles and the maximum peak vertical acceleration. The maximum values stated for the modified parameter runs are the maximum occuring at, or near, the same time as the baseline run maximums.



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 6 EXCEPTION NO. 3 IN VEHICLE TRAJECTORY AGREEMENT

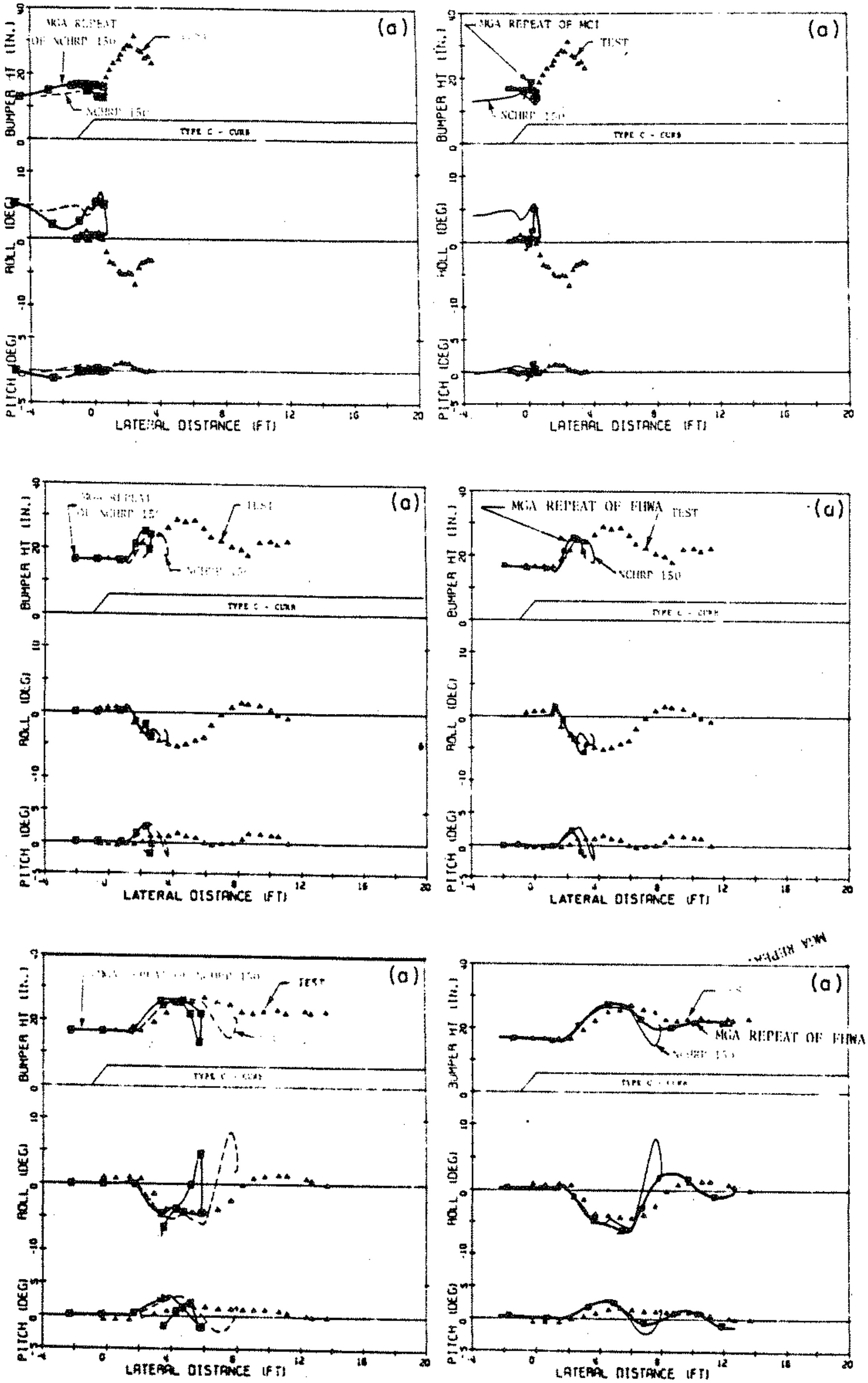


Figure 7 EXAMPLE OF INCREASING DIFFERENCES IN PREDICTED BUMPER HEIGHT, PITCH, & ROLL RESPONSES AS ENCROACHMENT ANGLE INCREASES

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Table 9

SENSITIVITY STUDY VARIATIONS

	Baseline Value	Variations
Suspension Damping	F1.3/R1.75*	F3.5/R3.9*, F0.6/R0.8*
Tire Bottoming Deflection	6.0	3.0
Sprung Mass Pitch Inertia	28678	32712, 14376
Sprung Mass Yaw Inertia	33029	39635, 28075
Steering System Inertia	300.0	100, 1000
Steering System Friction	5000.0	200, 1000
Rear Axle Roll Inertia	435.6	600.0
Suspension Friction	F58/R97*	F55/R50*

*Front and rear values, respectively

Table 10

SENSITIVITY STUDY RESULTS

Parameter Varied	Value(s)	Test	Approach Speed (mph)	Approach Angle (deg)	Max. Roll Angle[1] (deg)	Max. Pitch Angle[1] (deg)	Max. Peak Vert. Acc.[1] (G's)
Suspension Damping (Units: lb-s/in)	F1.3/R1.75[2]	N-2	30.4	5.1	-3.08	-1.00	0.37
	F0.6/R0.8	N-2	30.4	5.1	-2.85	-0.97	0.40
	F3.5/R3.9	N-2	30.4	5.1	-3.33	-0.92	0.34
	F1.3/R1.75[2]	N-10	63.0	17.6	8.88	2.88	-2.37
	F0.6/R0.8	N-10	63.0	17.6	10.30	2.50	-2.45
	F3.5/R.39	N-10	63.0	17.6	5.09	1.79	-2.11
Tire Bottoming Deflection (Units: in)	6.0[2]	N-2	30.4	5.1	-3.08	-1.00	0.37
	3.0	N-2	30.4	5.1	-3.08	-1.00	0.37
	6.0[2]	N-10	63.0	17.6	8.88	2.28	-2.37
	3.0	N-10	63.0	17.6	10.00	3.37	-4.24
	6.0[2]	N-15	32.1	17.4	-6.60	2.40	-3.47
	3.0	N-15	32.1	17.4	-5.55	3.34	-3.19
	6.0[2]	N-17	66.5	5.1	2.09	1.64	-1.69
	3.0	N-17	66.5	5.1	13.69	0.77	-0.82
Rear Axle Roll Inertia (Units: $lb\text{-}s^2\text{-}in$)	435.6	N-17	66.5	5.1	-10.57	1.64	-1.69
	600.0	N-17	66.5	5.1	-11.69	1.67	-2.74
Suspension Friction (Units: lb-in)	F58/R97	N-17	66.5	5.1	-10.57	1.64	-1.69
	F55/R50	N-17	66.5	5.1	-10.62	1.63	-1.68

1 Peak value occurring at or near the time of occurrance of the maximum value for the baseline run

2 Baseline values

1 $lb\text{-}s^2\text{-}in = 0.113\ N \cdot s^2 \cdot m$
1 lb-s/in = 17.86 kg·s/m
1 in = 25.4 mm
1 lb-in = 0.133 N·m

Table 10 SENSITIVITY STUDY RESULTS (CONTINUED)

Parameter Varied	Value(s)	Test	Approach Speed (mph)	Approach Angle (deg)	Max. Roll Angle[1] (deg)	Max. Pitch Angle[1] (deg)	Max. Peak Vert. Acc.[1] (G's)
Sprung Mass Pitch Inertia (Units: lb-s2-in)	28678[2]	N-2	30.4	5.1	-3.08	-1.00	0.37
	32712	N-2	30.4	5.1	-3.05	-1.04	0.37
	14376	N-2	30.4	5.1	-3.38	-1.04	0.36
	28678[2]	N-10	63.0	17.6	8.88	2.28	-2.37
	32712	N-10	63.0	17.6	8.93	2.25	-2.39
	14376	N-10	63.0	17.6	7.91	1.54	-2.34
	28678[2]	N-15	32.1	17.4	-6.60	2.40	-3.47
	32712	N-15	32.1	17.4	-6.57	2.26	-3.45
	14376	N-15	32.1	17.4	-6.59	2.81	-3.58
	28678[2]	N-17	66.5	5.1	-10.57	1.64	-1.69
	32712	N-17	66.5	5.1	-10.11	1.49	-2.89
	14376	N-17	66.5	5.1	-12.01	2.60	-2.11
Sprung Mass Yaw Inertia (Units: lb-s2-in)	33029[2]	N-2	30.4	5.1	-3.08	-1.00	-0.23
	39635	N-2	30.4	5.1	-3.93	-1.09	-0.34
	28075	N-2	30.4	5.1	-2.30	-2.27	-2.65
	33029[2]	N-10	63.0	17.6	8.88	2.28	-2.37
	39635	N-10	63.0	17.6	8.66	2.28	-2.37
	28075	N-10	63.0	17.6	8.99	2.26	-2.37
	33029[2]	N-15	32.1	17.4	-6.60	2.40	-3.47
	39635	N-15	32.1	17.4	-6.60	2.42	-3.48
	28075	N-15	32.1	17.4	-6.60	2.40	-3.45
	33029[2]	N-17	66.5	5.1	-10.57	1.64	-1.69
	39635	N-17	66.5	5.1	-10.48	1.73	-2.61
	28075	N-17	66.5	5.1	-10.46	1.58	-1.67

[1] Peak value occurring at or near the time of occurrance of the maximum value for the baseline run

[2] Baseline values

1 $lb \cdot s^2$-in = 0.113 $N \cdot s^2 \cdot m$

Table 10 SENSITIVITY STUDY RESULTS (CONTINUED)

Parameter Varied	Value(s)	Test	Approach Speed (mph)	Approach Angle (deg)	Max. Roll Angle[1] (deg)	Max. Pitch Angle[1] (deg)	Max. Peak Vert. Acc.[1] (G's)
Steering System Friction (Units: lb-in)	5000[2]	N-2	30.4	5.1	2.12	0.66	-2.3
	200	N-2	30.4	5.1	2.17	1.77	-0.24
	1000	N-2	30.4	5.1	2.13	0.73	-0.30
	5000[2]	N-10	63.0	17.6	8.88	2.28	-2.37
	200	N-10	63.0	17.6	9.65	2.15	-2.37
	1000	N-10	63.0	17.6	9.01	2.22	-2.37
	5000[2]	N-15	32.1	17.4	-6.60	2.40	-3.47
	200	N-15	32.1	17.4	-4.42	2.32	-3.48
	1000	N-15	32.1	17.4	-5.12	2.35	-3.48
	5000[2]	N-17	66.5	5.1	-10.57	1.64	-1.69
	200	N-17	66.5	5.1	-8.86	1.64	-1.73
	1000	N-17	66.5	5.1	-9.38	1.64	-1.71
Steering System Inertia (Units: lb-s²-in)	300[2]	N-2	30.4	5.1	-3.08	-1.00	0.37
	100	N-2	30.4	5.1	-3.09	-1.04	0.36
	1000	N-2	30.4	5.1	-2.45	-1.03	0.34
	300[2]	N-10	63.0	17.6	8.88	2.28	-2.37
	100	N-10	63.0	17.6	8.78	2.28	-2.37
	1000	N-10	63.0	17.6	9.08	2.26	-2.37
	300[2]	N-15	32.1	17.4	-6.60	2.40	-3.47
	100	N-15	32.1	17.4	-5.70	2.42	-3.56
	1000	N-15	32.1	17.4	-6.59	2.39	-3.44
	300[2]	N-17	66.5	5.1	-10.57	1.64	-1.69
	100	N-17	66.5	5.1	-9.70	1.67	-1.72
	1000	N-17	66.5	5.1	-10.37	1.64	-1.60

[1] Peak value occurring at or near the time of occurrance of the maximum value for the baseline run

[2] Baseline values

1 lb-in = 0.113 N·m
1 lb-s²-in = 0.113 N·s²·m

The parameter changes which caused noticeable (10 percent or greater) differences in one or more of the maximum values results are as follows:

- The changes in suspension damping affected the results for high-speed impact. The changes involved the increasing of the front and rear suspension damping values to 3.5 lb-s/in (62.5 kg s/m) and 3.9 lb-s/in (69.6 kg s/m) respectively, and decreasing them to 0.6 lb-s/in (10.7 kg s/m) and 0.8 lb-s/in (14.3 kg s/m) respectively from their original values of 1.3 lb-s/in (31.3 kg s/m) and 1.75 lb-s/in (31.3 kg s/m) respectively. (Both of these parameter changes affected the results.)

- It was seen that a decrease in tire bottoming deflection from 6.0 in (152.4 mm) to 3.0 in (76.2 mm) affected the results of all cases where there is a high component of velocity perpendicular to the curb (i.e., high angle/low speed, high angle/high speed, and low angle/high speed.)

- Rear axle roll inertia did cause a change in peak vertical acceleration when increased from 435.6 lb-s^2-in (49.2 N s^2 m) to 600.0 lb-s^2-in(67.8 N s^2 m). This resulted from a momentary bump stop contact.

- Decreasing the sprung mass pitch inertia by nearly 50 percent from 28,678 lb-s^2-in (3.2 kN s^2 m) to 14,376 lb-s^2-in (1.6 kN s^2 m) did affect angular responses for runs. Peak accelerations were not affected. Also, an increase from 28,678 lb-s^2-in (3.2 kN s^2 m) to 32,712 lb-s^2-in (3.7 kN s^2 m) did affect the low-speed/high-angle case.

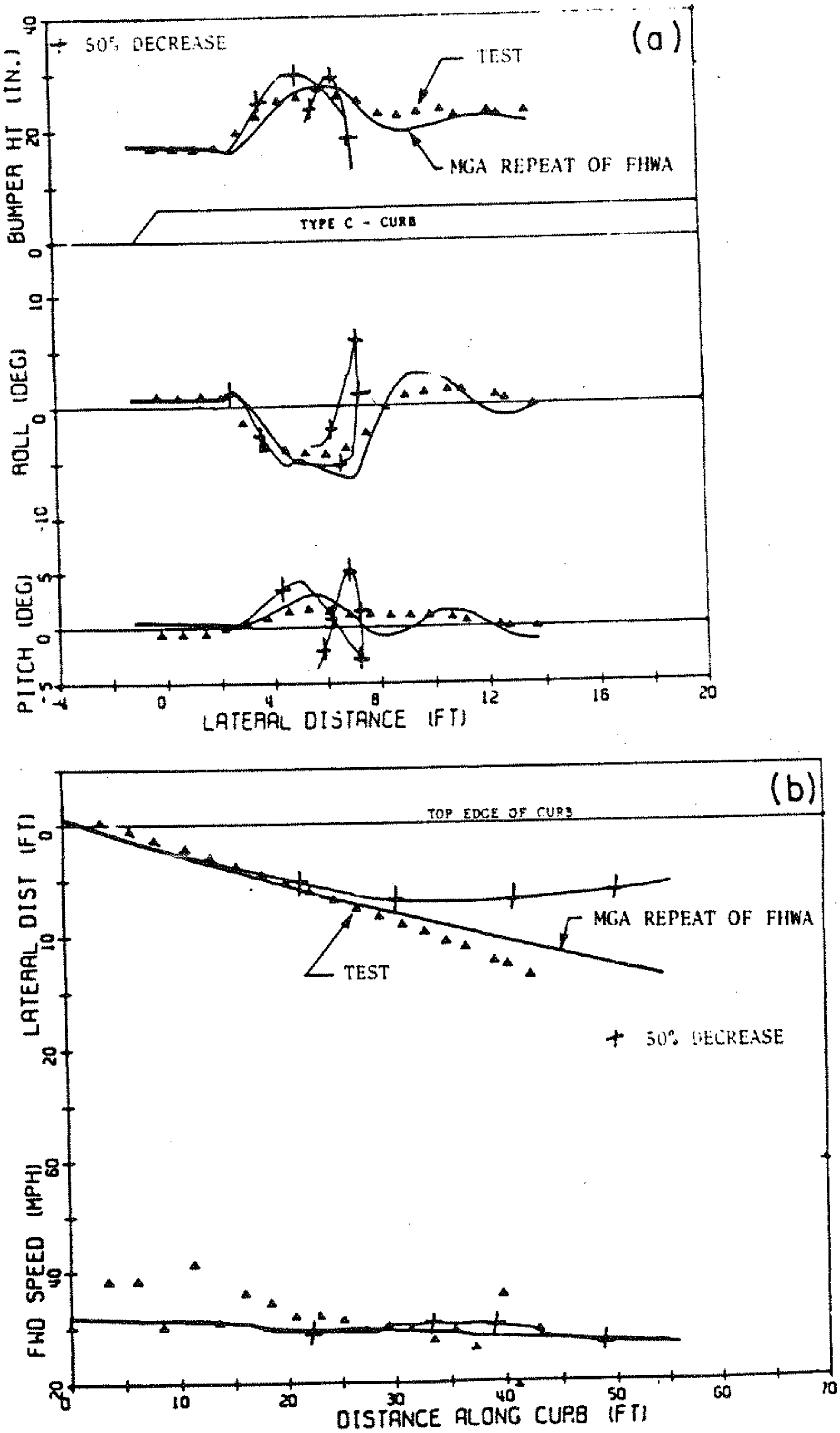
- Sprung mass yaw inertia changes have affected the results of the low-impact angle cases. Principal differences occur in peak acceleration values where slight changes in bump stop engagement produce large short duration changes in vertical accelerations.

- Steering system friction angular response results differ for all runs. Peak acceleration responses are not affected, however, by friction changes.

- Changes in the steering system inertia changes causes differences in the angular response tabulated for the type C curb impacts when the value is decreased from 300 $lb\text{-}s^2\text{-}in$ (33.9 $N\ s^2\ m$) to 100 $in\text{-}s^2\text{-}in$ (11.3 $N\ s^2\ m$) and for the low-speed/low angle impact when the value is increased from 300 $lb\text{-}sec^2\text{-}in$ (33.9 $N\ s^2\ m$) to 1,000 $lb\text{-}s^2\text{-}in$ (113.0 $N\ s^2\ m$).

Table 10 has pointed out the parameter changes which appear to be possible causes for the differences among the various sets of results. In order to firmly establish which parameters cause differences, the graphical results have been prepared. (The full set of plots are given in appendix C.) The graphical results allow the visual interpretation of the differences in the tabulated results as well as showing to what extent the differences are significant. The agreement between the information in table 3-10 and the graphical results is generally good. The following is a summary of the interpretation of the graphical results:

- The tire bottoming deflection parameter change (from 6.0 in (152.4 mm) to 3.0 in (76 mm) causes dramatic changes in vehicle trajectory as well as in bumper height, roll angle, etc. An example of this is shown in figure 8.



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

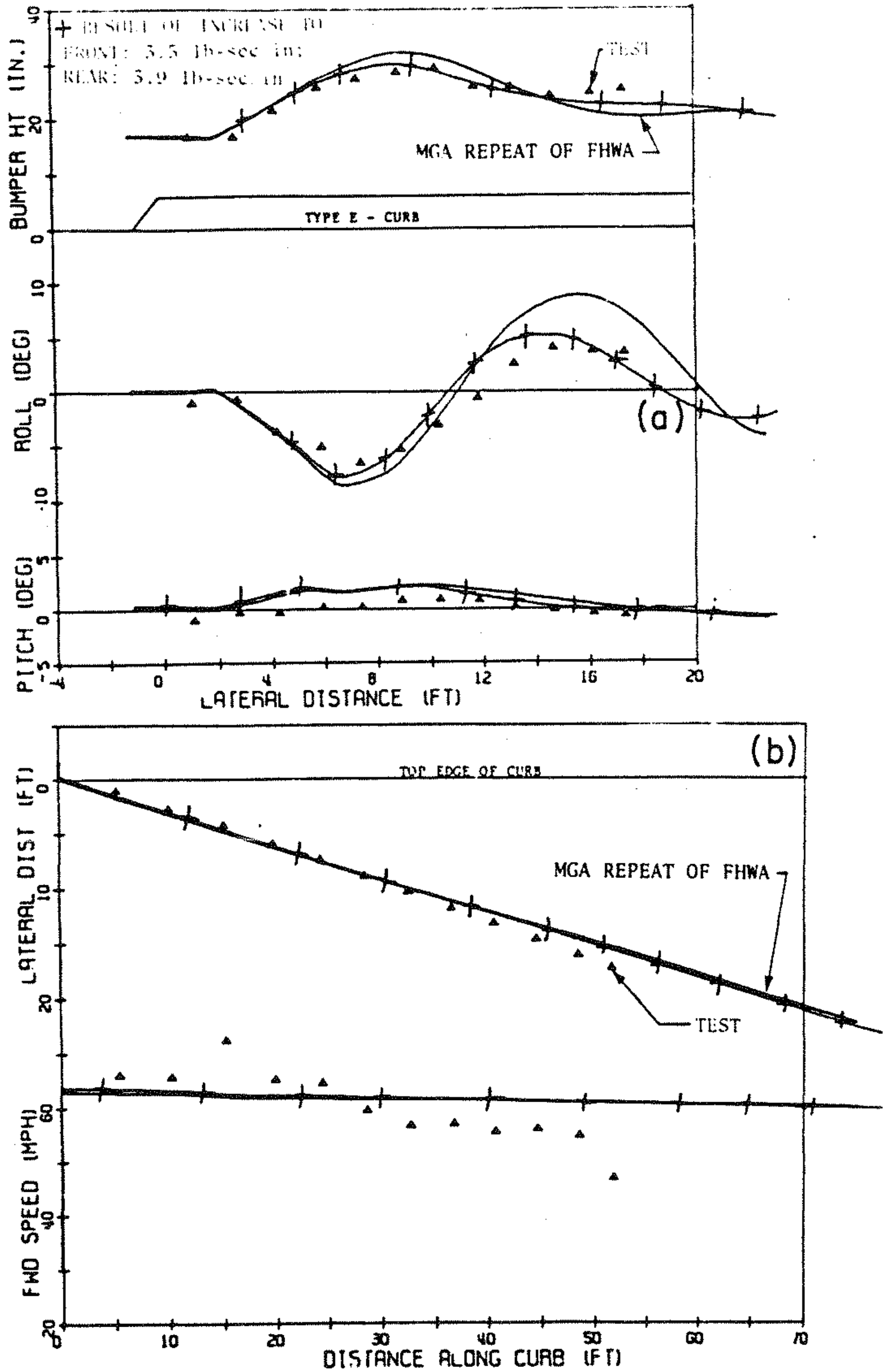
Figure 8 RESULTS OF TIRE BOTTOMING DEFLECTION REDUCTION IN TEST N-15: (A) VEHICLE ROLL, PITCH AND BUMPER HEIGHT; (B) VEHICLE SPEED & PATH

- Some modest changes in vehicle response occur when the value is of suspension damping is changed for the high speed/high-angle case. No changes in vehicle redirection were caused by these changes. (figures 9 and 10)

- Rear axle roll inertia did produce a modest change in the vehicle roll response when the value was increased from 435.6 lb-s2-in (49.2 N s2 m) to 600.0 lb-s2-in (67.8 N s2 m). The difference is particularly noticeable toward the end of the simulated event. (figure 11) This response change was somewhat unexpected. Upon reviewing the run involved, it became apparent that the change in roll response was due to a large momentary force experienced by the right rear suspension. This large suspension force (roughly 50 percent higher than the baseline run) came from the interaction between the rear axle and the suspension bump stop. The increase in the inertia value allowed the rear axle to engage the bump stop further. The increased engagement was 0.2 inch (5.1 mm). This indicates that the change in roll response is an indirect result of the rear axle roll inertia change, and a direct function of the bump stop stiffness.

- Sprung mass pitch inertia changes produced changes in bumper height, roll angle, and pitch angle responses only when an extreme condition (50 percent decrease) was simulated. Trajectory in the plan view was not affected, even in this case. (figure 12). Figure 13 shows the extent of a 14 percent increase in the pitch inertia value for the high speed/low angle case. In this case the noticeable difference in the numerical data is not as apparent in the graphical data.

- Sprung mass yaw interia is another example where the numerical data alone could be misleading. From table 7 the difference in



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 9 RESULTS OF SUSPENSION DAMPING INCREASE IN TEST N-10: (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH

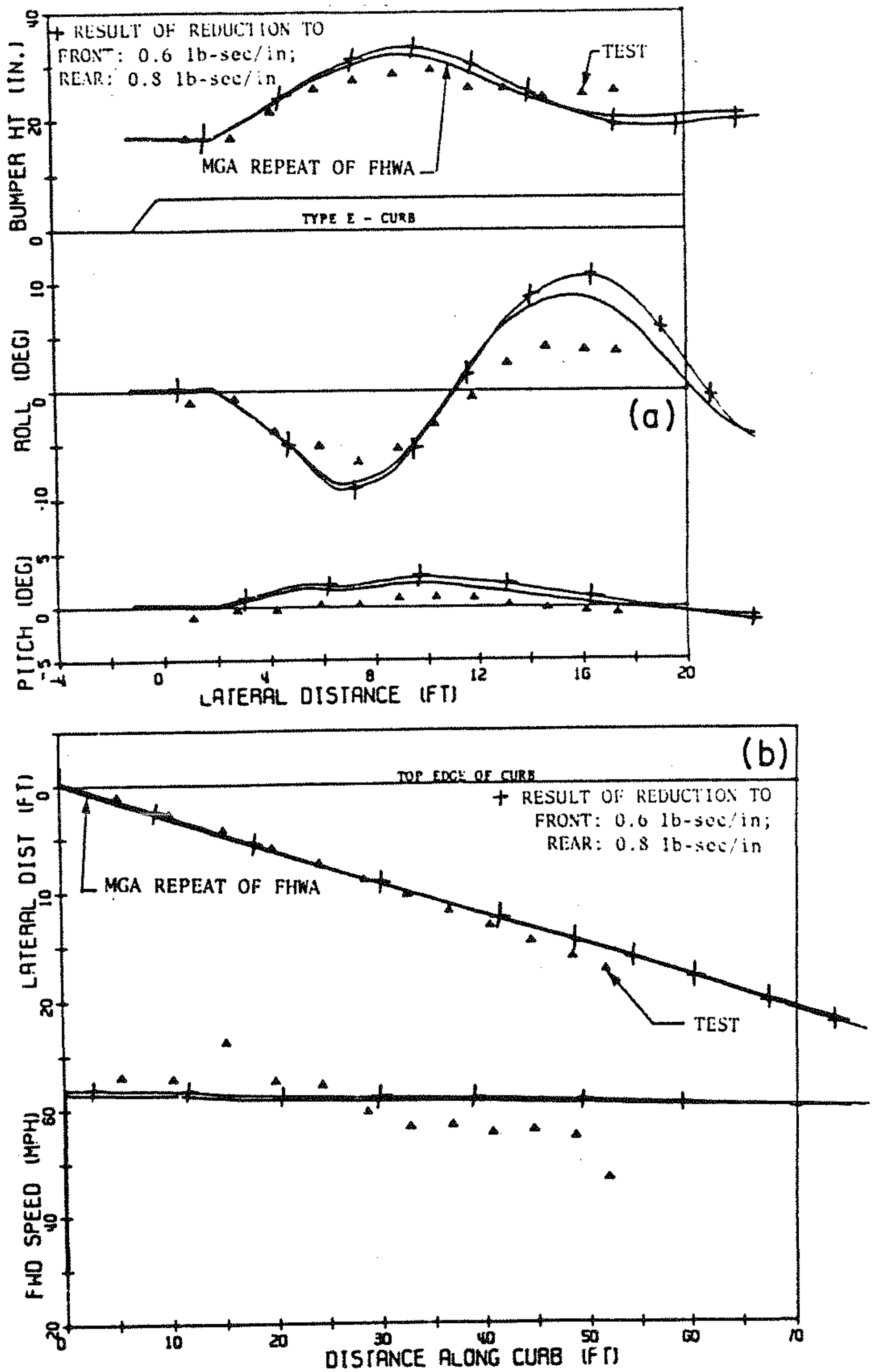


Figure 10 RESULTS OF SUSPENSION DAMPING DECREASE IN TEST N-10: (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

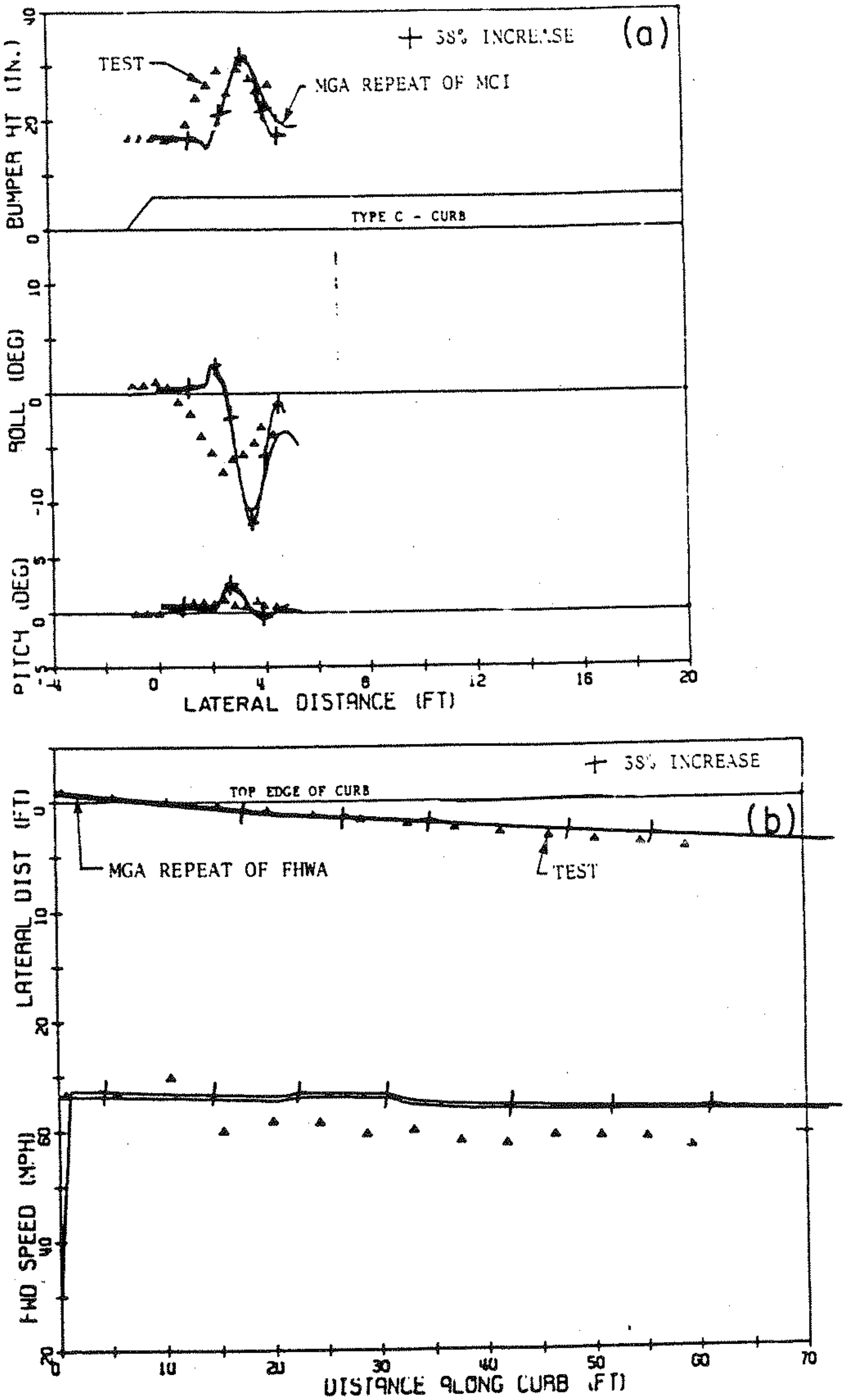


Figure 11 **RESULTS OF REAR AXLE ROLL INERTIA INCREASE IN TEST N-17: (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH**

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

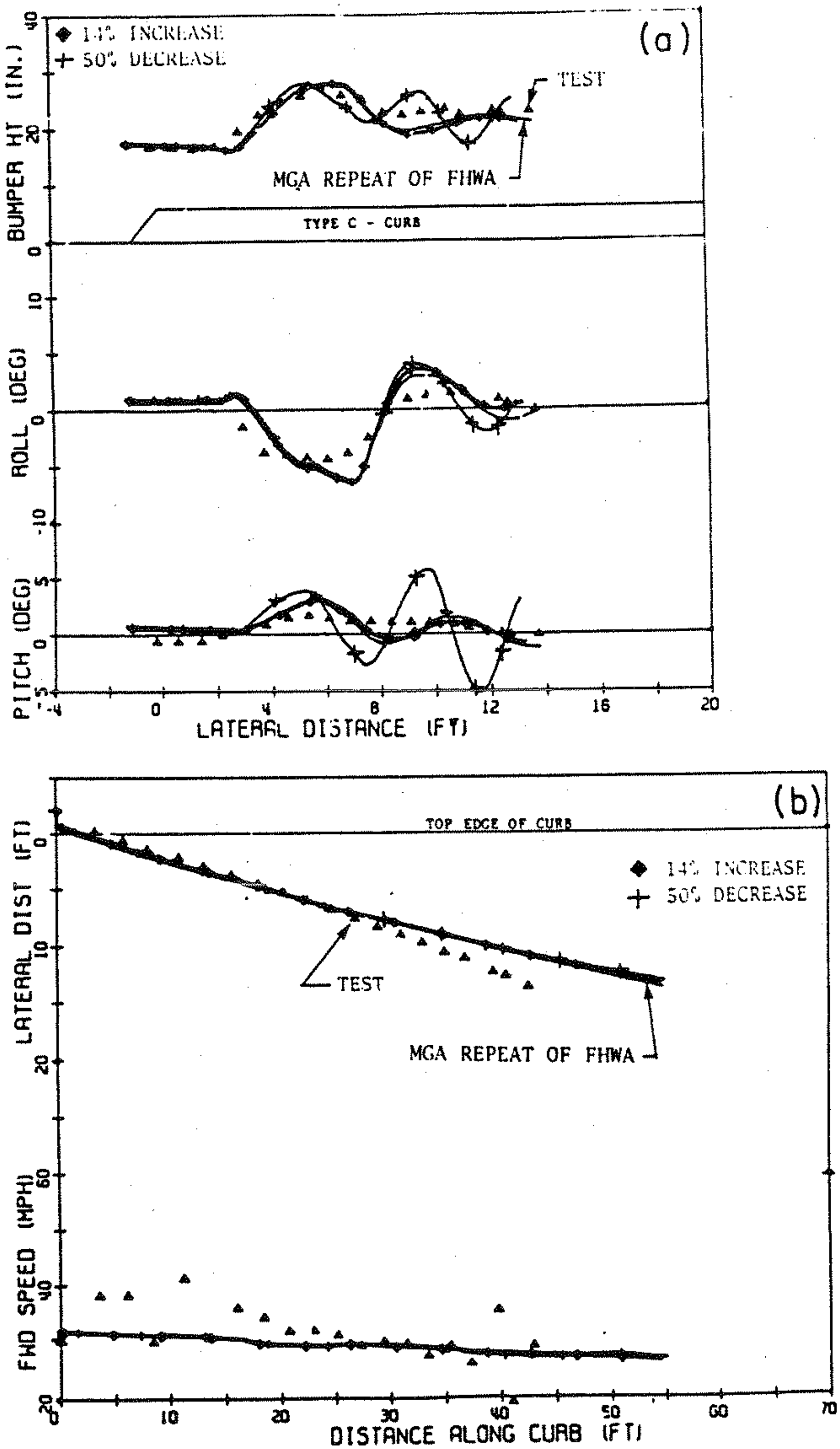
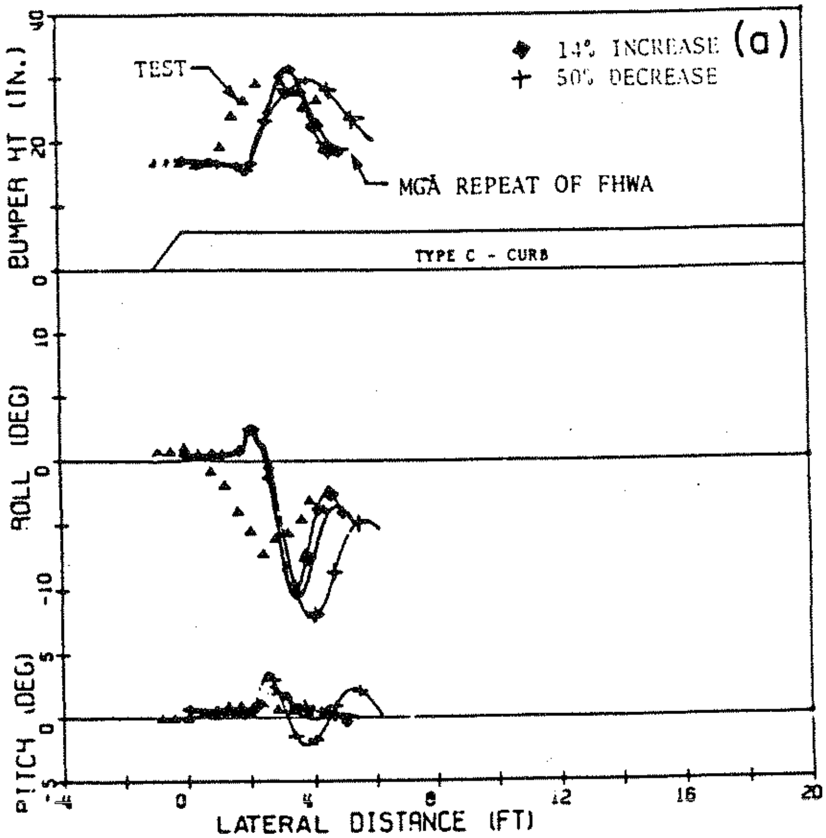


Figure 12 RESULTS OF SPRUNG MASS PITCH INERTIA CHANGES IN TEST N-15: (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h



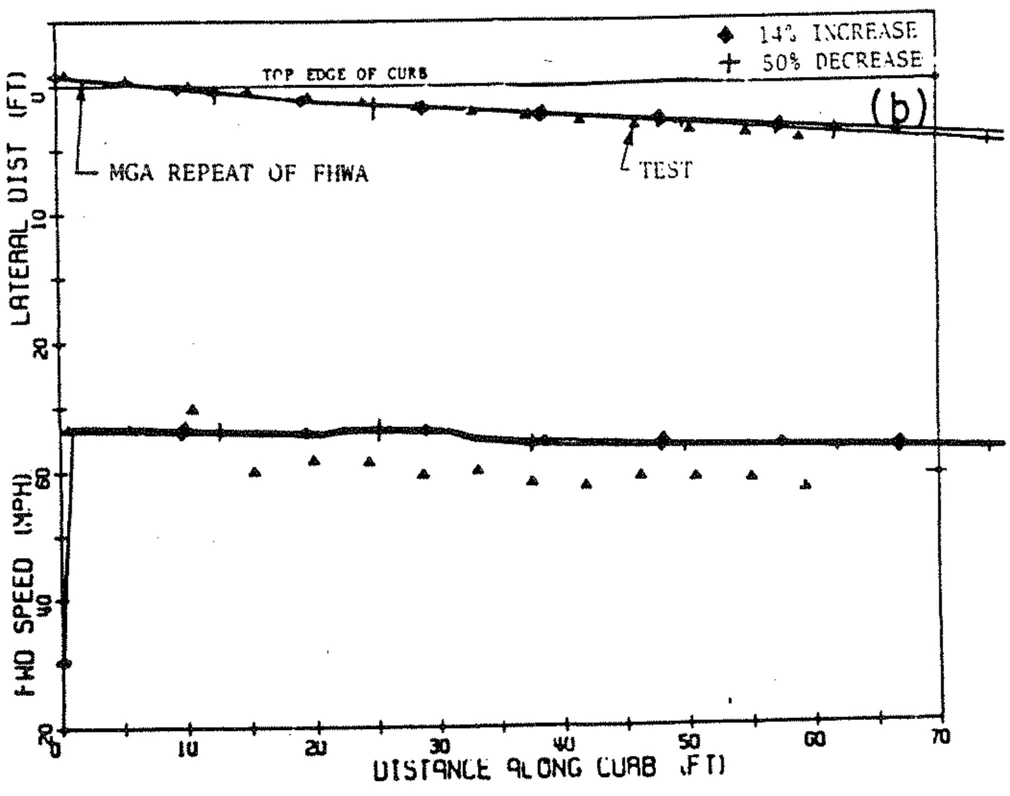


Figure 13 RESULTS OF SPRUNG MASS PITCH INERTIA CHANGES IN TEST N-17: (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH

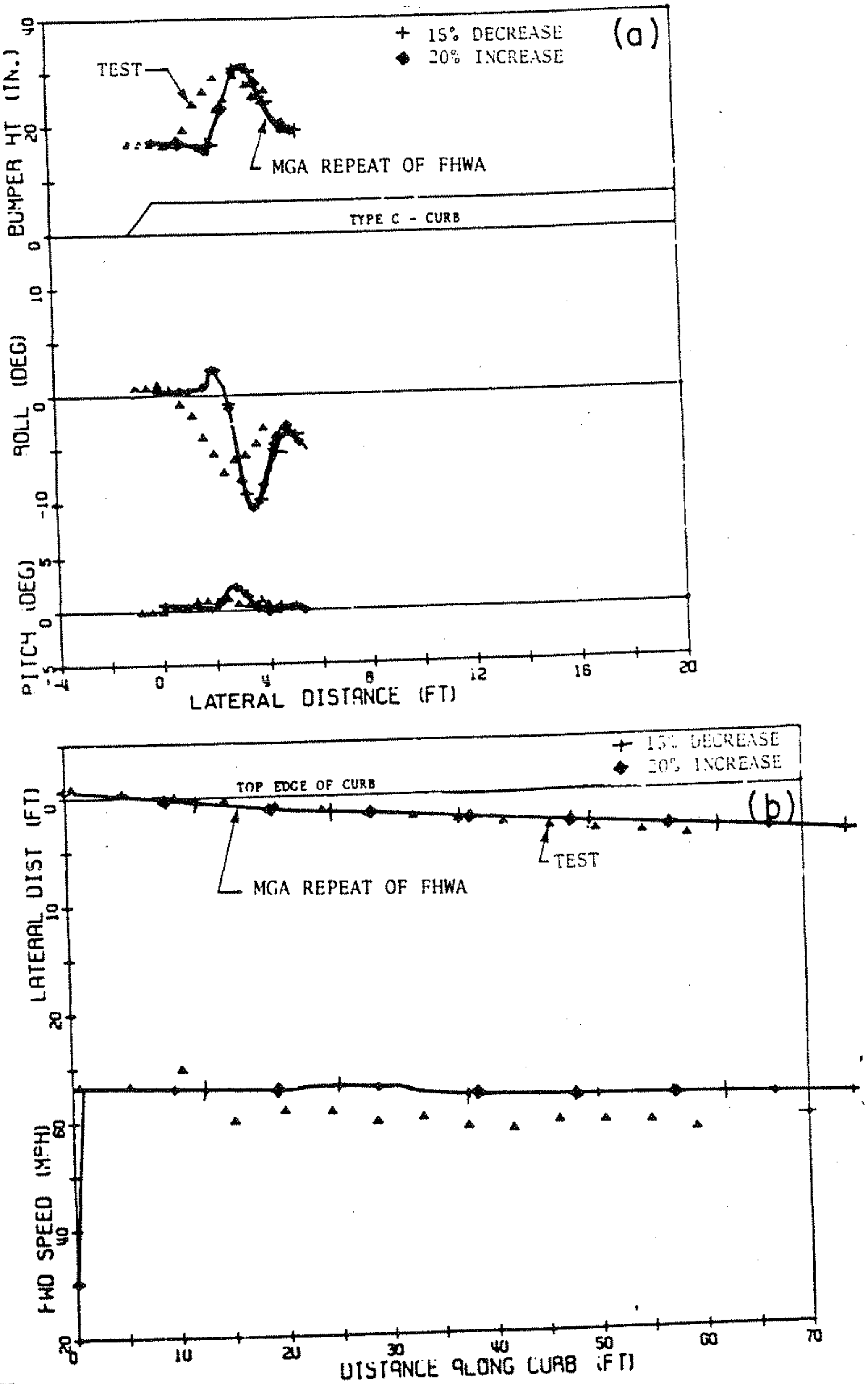
1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

in results indicates that a change in yaw inertia from 33,029 lb-s^2-in (3.7 kN s^2 m) to 39,635 lb-s^2-in (4.5 kN s^2 m) could be significant, while figure 14 shows that there are essentially no differences in results. Figure 15 also indicates that modest changes in yaw inertia do not substantially affect the general vehicle responses.

- Steering system friction was found to be an important variable in terms of vehicle response in both the numerical and graphical results. Figure 16 is an example of the dramatic trajectory changes that were apparent in some cases. The changes, both decreases from 5,000 lb-in (565 N m) caused vehicle response changes which were most evident in the type C impacts (runs N-15 and N-17). The trajectory changes, however, were confined to the low-speed impacts.

- The graphical results for steering system inertia show that only a decrease from 300 lb-s^2-in (33.9 N s^2 m) to 100 lb-s^2-in (11.3 N s^2 m) affects the results, and then only for the Type C curb impacts. Such a change produced changes in plan view trajectory as well as to roll and pitch angle responses. Figure 17 is an example of the changes caused by changing the steering system inertia value.

Along with showing those parameters for which changes cause differences in the simulation results, the sensitivity study has also shown that some response changes are curb dependent. This becomes important in explaining why, in general, the FHWA study data predicts values closer to the test results for the type C curb impacts and the NCHRP study data predicts values closer to the test results for some of the type E curb impacts.



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 14 RESULTS OF SPRUNG MASS YAW INERTIA CHANGES IN TEST N-17: (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH

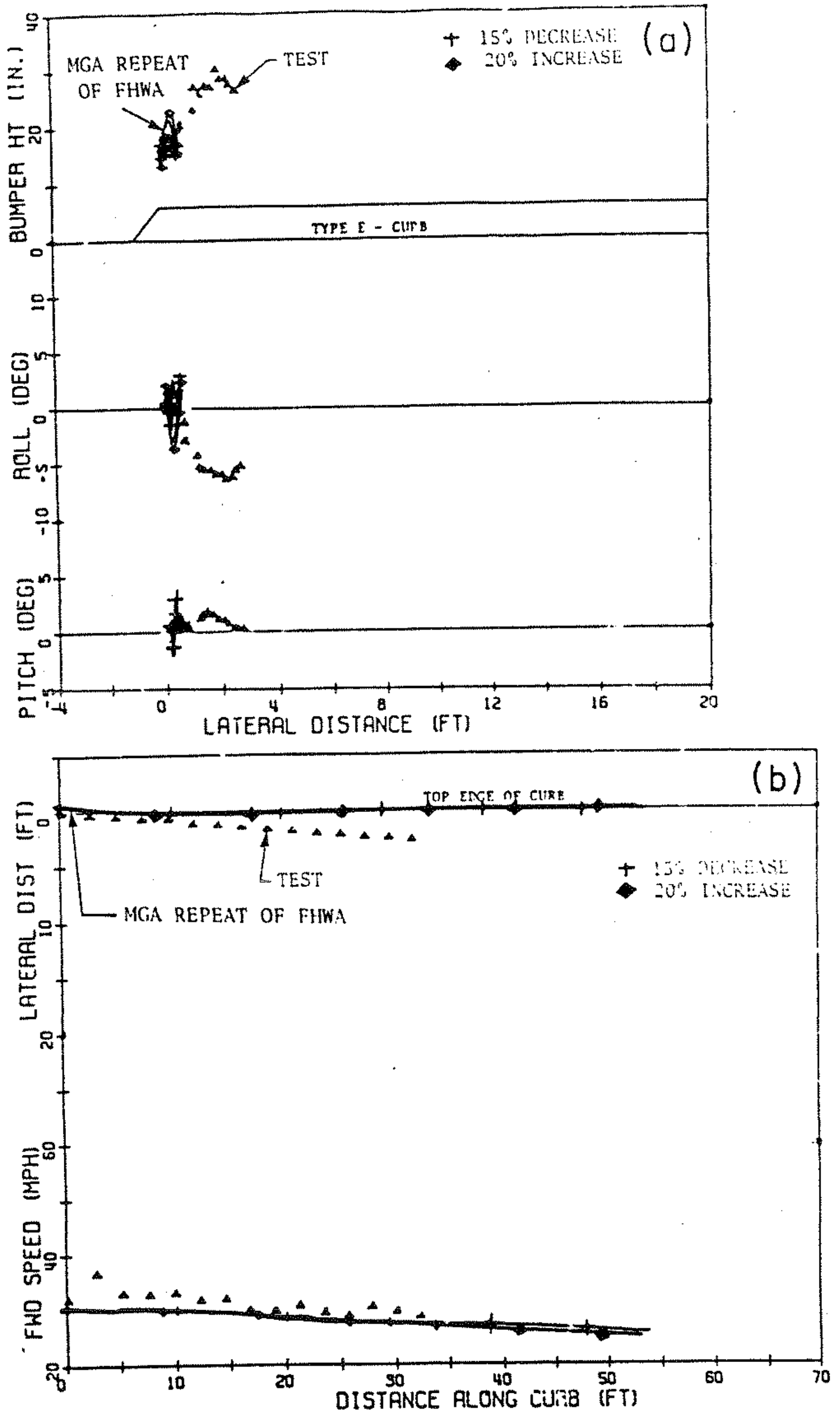
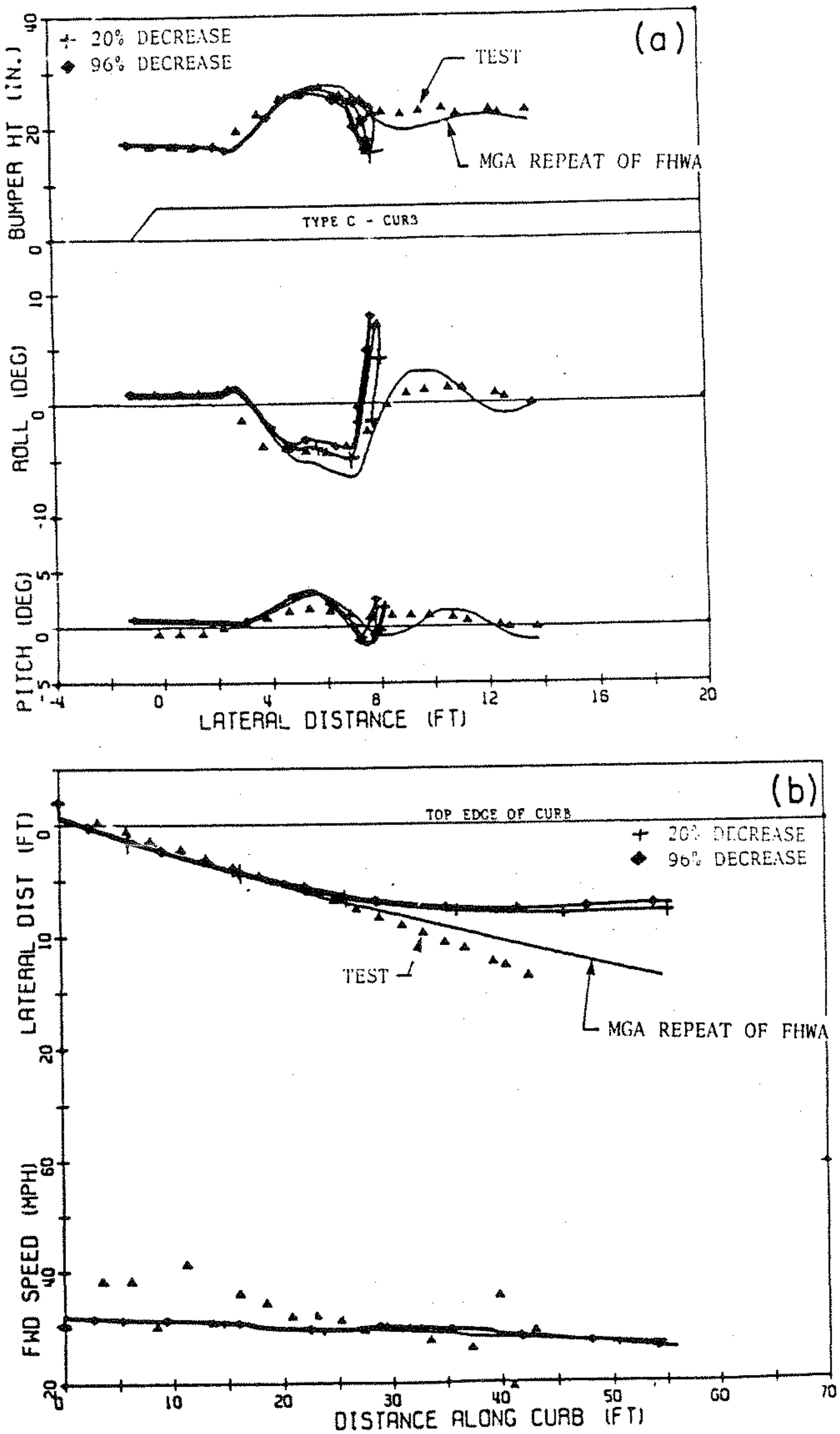


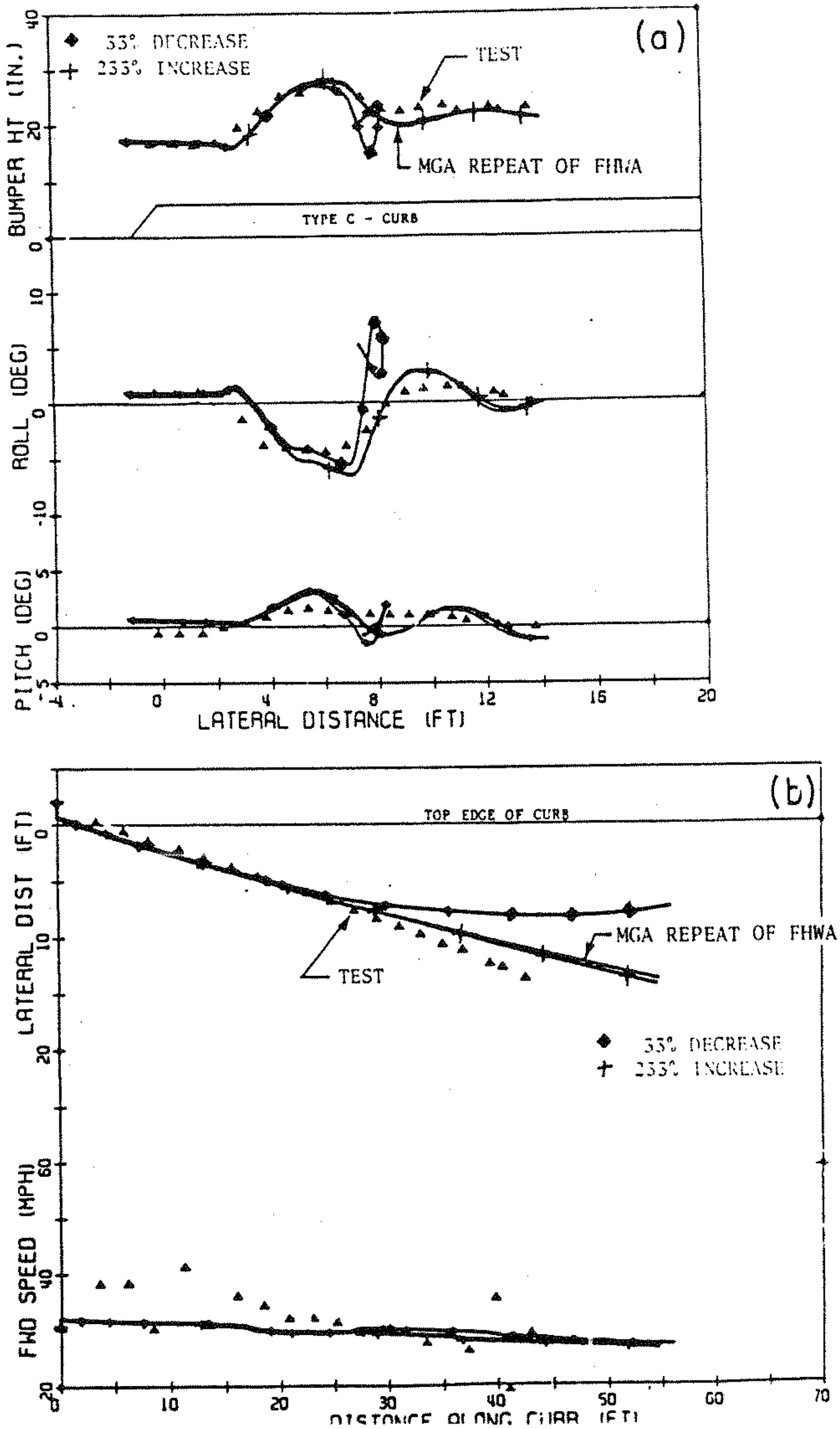
Figure 15 RESULTS OF SPRUNG MASS YAW INERTIA CHANGES IN TEST N-2: (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 16 RESULTS OF STEERING SYSTEM FRICTION CHANGES IN TEST N-15: (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 17 RESULTS OF STEERING SYSTEM INERTIA CHANES IN TEST N-15 (A) VEHICLE ROLL, PITCH & BUMPER HEIGHT; (B) VEHICLE SPEED & PATH

3.4 Development of Best Available Data Set

In reviewing the data presented in section 3.1, it is clear that discrepancies in parameter values exist betwe· the previous studies data sets in ˋ ɩuˉber of areas. The intent of this sec on is to identify those values which best represent the vehicle in question for simulation of curb impacts. This includes evaluation of previous data, sensitivity of results to data variations, and measurement of certain vehicle characteristics.

The parameter values that are judged the best available to represent the 1963 Ford Galaxie used in the NCHRP curb traversal tests are summarized along with previous studies data, ın tables 11 through 13. Inertial and dimensional data are listed in table 11. As is seen there, the major differences in values across the data sets in the sprung mass moments of inertia. In the absence of actual vehicle measurements, the values computed in the FHWA study were based on regressions of typical vehicle parameters and by assuming a constant vehicle radius of gyration while changing total mass are judged to be more appropriate as a firm basis is available. The rear axle roll inertia (I_R) used by in the FHWA study was also judged more appropriate as it does reflect a measurement of the parameter value as reported in Ref. 2.

Suspension rate data is shown in figure 12. In this case, both previous studies used data which produced identical suspension rate characteristics. Hence, the best available data reflects this same information.

Additional suspension and steering data are shown in table 13. Friction and damping values selected for the best data set runs were those used in the NCHRP study. These values were also used in the original HVOSM validation effort (Ref. 2). Similarly, auxiliary roll stiffnesses and rear axle roll steer were selcted based on their use in previous HVOSM validation efforts.

Table 11

INERTIAL AND DIMENSION DATA

Variable	Units	"Best" Data Set
M_S	lb sec^2/in	9.318
M_{UF}	lb sec^2/in	0.590
M_{UR}	lb sec^2/in	0.961
I_X	lb sec^2-in	5028
I_Y	lb sec^2-in	28678
I_Z	lb sec^2-in	33029
I_{XZ}	lb sec^2-in	-192
I_R	lb sec^2-in	435.6
a	in.	54.55
b	in.	64.45
T_F	in.	61.0
T_R	in.	60.0
	in.	-2.0
T_S	in.	46.5
Sprung Mass CG Height	in.	24.14

1 lb-s^2/in = 17.86 kg·s^2/m
1 in = 25.4 mm
1 lb-s^2-in = 0.113 N·s^2·m

Table 12

SUSPENSION RATE DATA

Variable	Units	"Best Data Set
K_F	lb/in	131
K_{FC}	lb/in	300
K'_{FC}	lb/in^3	600[1]
K_{FE}	lb/in	300
K'_{FE}	lb/in^3	600[1]
F	-	0.5
FC	in	-3
FE	in	5
K_R	lb/in	192
K_{RC}	lb/in	300
K'_{RC}	lb/in^3	600
K_{RE}	lb/in	300
K'_{RE}	lb/in^3	600
R	-	0.5
RC	in	-4
RE	in	4.5

1 Expressed in HVOSM-RD2 equivalent values.

1 lb/in = 17.86 kg/m
1 lb/in^2 = 27680 kg/m^3
1 in = 25.4 mm

Table 13

SUSPENSION AND STEERING DATA

Variable	Units	"Best" Data Set
C_F	(lb-sec/in)	3.5
C_F'	(lb)	55
F	(in/sec)	.001
C_E	(lb-sec/in)	3.9
C_R'	(lb)	50
R	(in/sec)	.001
R_F	(lb-in/rad)	266000
R_R	(lb-in/rad)	61900
KRS		0.07
I	(lb-sec2-in)	228
C'	(lb-in)	650
	(rad)	0.4
K	(lb-in/rad)	50000
E	(rad/sec)	0.075
P	(in)	1.5

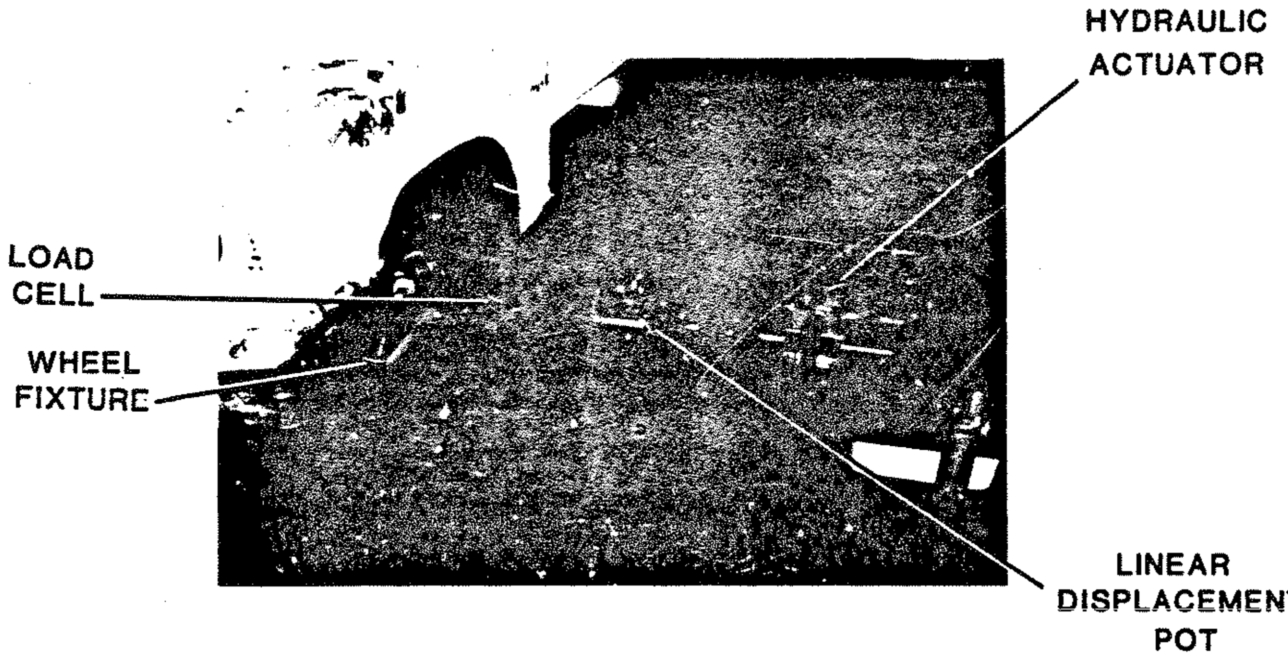
1 lb-s/in = 17.86 kg·s/in
1 lb = 0.454
1 in/s = 0.025 m/s
1 lb·in/rad = 0.133 N·m/r
1 lb-s2·in = 0.133 N·s2·m
1 lb·in = 0.133 N·m
1 in = 25.4 mm

Of the steering system data, the angular stop location and stop stiffness are not factors in the run results for the situations considered in the validation study; in no case were the stops engaged. The pneumatic trail could not be estimated with any more confidence that the value of 1.5 inches (38.1 mm) used by in the FHWA study without additional aligning torque data for the tires used on the test vehicle. It is, however, recognized that the use of a constant pneumatic trail injunction with the lateral tire force does not adequately represent aligning torque characteristics at high lateral force values.

Both the steering system moment of inertia and friction had the potential for influencing front wheel steer angle and, therefore, vehicle trajectory to a significant degree. Therefore, physical testing on a 1963 Ford was carried out to measure the steering system moment of inertia and the steering system hysteresis (the amount of friction torque within the steering system).

The first test carried out was the measurement of the moment of inertia for the steering system. Since it was impractical to measure the inertia by the direct measurement of the steering system components, the "effective" moment of inertia was indirectly measured by use of a forced oscillation method. In this method, the effective moment of inertia of the system can be indirectly determined by adding springs of a known spring rate to the system and measuring the system's natural frequency. From the natural frequency and the known rate, the interia can be determined using the relationship $\omega = \frac{S}{I}$ where S is the stiffness or spring rate of a torsional system, ω is the natural (circular) frequency, and I is the system inertia.

For this test, the front driver's side wheel excited around its pivot axis by a hydraulic actuator. (figure 18) The restoring force was provided by a torsion bar attached to the system via the steering tie rods. This torsion bar was secured by two frames which transferred the loads to the



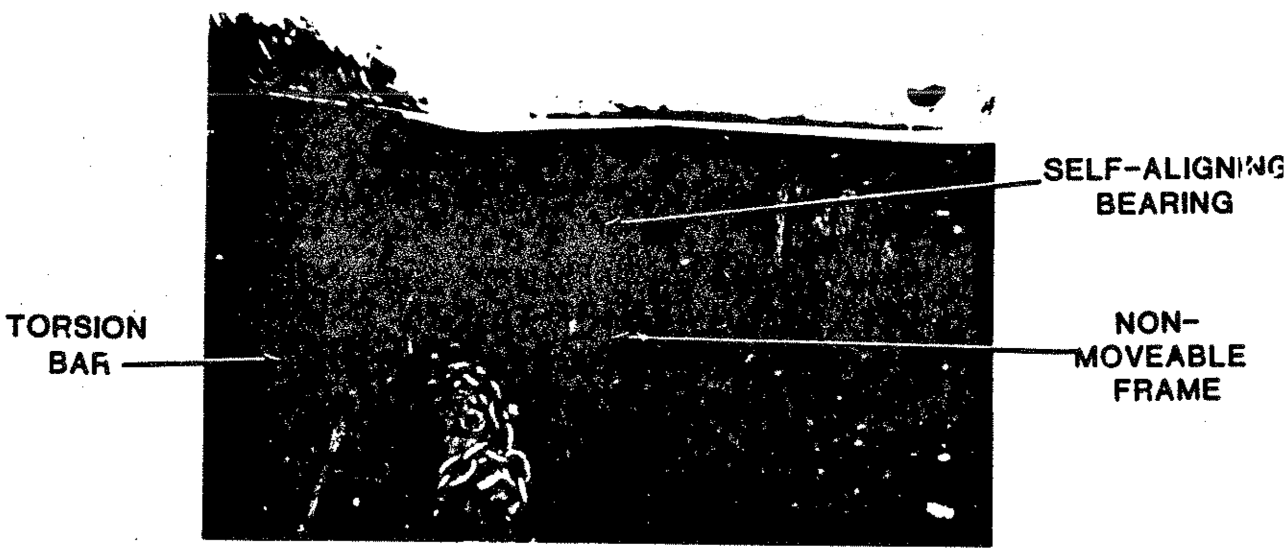
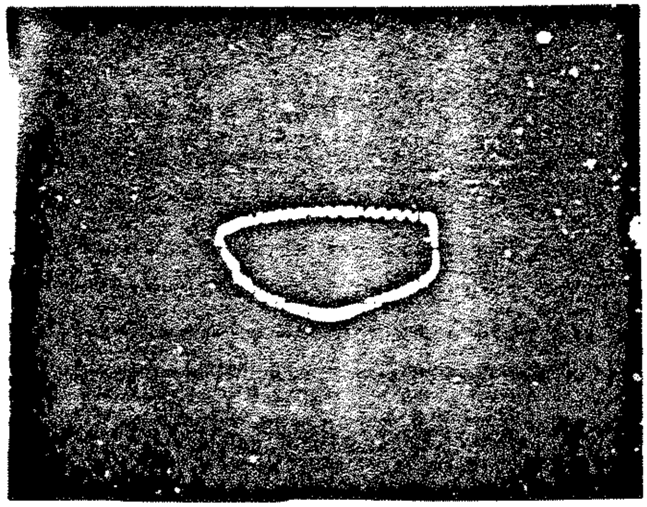


Figure 18 EXPERIMENTAL SET-UP FOR MEASURING THE STEERING SYSTEM MOMENT OF INTERIA

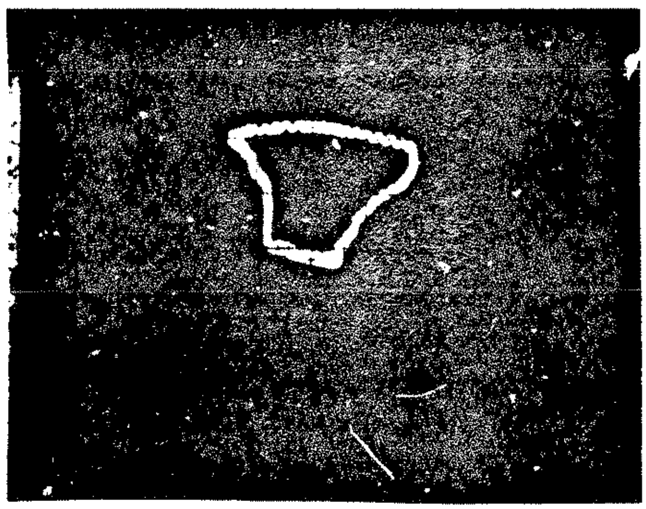
floor. The outermost frame was clamped to the bar thus providing an end restraint and thereby fixing the stiffness of the bar. This frame was adjustable so that inertia could be measured at various rates of stiffness for the sytem. The other frame was not movable but instead provided support and aided in keeping the torsion bar from bending rather than twisting as was intended. This was done with the use of a self-aligning bearing attached between the torsion bar and frame. The driving force was measured by a load cell and the response to this force was measured via a linear displacement potentiometer. The signals from these two devices were fed into an oscilloscope such that the force would be displayed on the horizontal axis and the displacement on the vertical axis.

The natural frequency of the system was determined as that shaking frequency (as provided by the Moog D-C Servocontroller) which resulted in a 90-degree phase lag of the displacement with respect to the applied shaking force. This 90-degree phase lag shows up a figure on the oscilloscope which is symmetric about the vertical axis. (figure 19) Upon start up of the test, it was noticed that the steering wheel was not totally involved in the system; therefore, the steering box tightened so as to reduce the amount of "play" in the steering system. After that was done, the test was carried out at various torsion bar lengths. The values for the natural frequency for the system at these lengths are shown in table 14. This table represents the expected result that as the induced spring rate (stiffness) decreases, the values of natural frequency would have to decrease so that the value of inertia would remain a constant. When the information in table 3-14 is extended out to show both stiffness and the resultant inertia value, it was seen that the inertia value did not remain constant as was expected. Even though the value for inertia is not constant, table 15 does show that the value lies within the range of 200 to 400 lb-s2-in (22.6 - 45.2 N s2 m). This range of values is lower than the value used is in either previous studies.

It is not clear why stiffness changes resulted in such a large change in calculated inertia but a number of possible factors include



a) PATTERN AT TORSION BAR LENGTH = 155 INCHES



b) PATTERN AT TORSION BAR LENGTH = 119 INCHES

1 in = 25.4

Figure 19 OSCILLOSCOPE PATTERN OF THE FORCED RESPONSE VERSUS THE SHAKING FORCE AT SHAKING FREQUENCY NATURAL FREQUENCY

Table 14

VALUES OF NATURAL FREQUENCY AT VARIOUS TORSION BAR LENGTHS

Length of Torsion Bar		Natural Frequency
Nominal (in)	Actual (in)	Hz
72	71.5	0.66
120	119	0.62
156	155	0.61

1 in = 25.4

Tabla 15

DETERMINATION OF MOMENTS OF INERTIA FOR THE VARIOUS TORSION BAR LENGTHS

Actual Length (in)	Measured Frequency (Hz)	Measured Torsional Stiffness (in lb/rad)	Calculated Inertia Values (lb s2 in)
71.5	0.66	6,711	390
119.0	0.62	4,103	270
155.0	0.61	2,995	204

1 in = 25.4 mm
1 in·lb/rad = 0.113 N·m/r
1 lb·s^2·in = 0.113 N·s^2·m

excessive play in system components (e.g., tie-rods, ball-joints), high levels of friction, bending as well as twisting of the torsion bar, and high levels of damping induced by excitation of the power steering systems. Nonetheless, it seems apparent that values of steering system moments of inertia of 200 to 600 lb-s^2-in (22.6 to 67.8 N s^2 m) are reasonable values for a vehicle of the size considered.

The second test carried out was the measurement of the steering system friction torque. This was accomplished by causing the front driver's side wheel to rotate around its pivot axis. This was done by applying a force to the outside edge of the rim so that the wheel made one complete cycle between the steering stops. (figure 19) The applied force and resulting deflection were measured by a load cell and a linear displacement pot, respectively. The signals produced by these instruments were than fed into a plotter so that the force was displayed on the vertical axis and the displacement on the horizontal axis. The two plots were then digitized and the values were resolved, by means of the geometary of the set up, into the corresponding applied torque and angle of rotation of the wheel about the wheel's centerline. Figures 20 and 21 are the resulting plots. The value of friction torque was then obtained from these plots since the friction torque at any given angle is half the difference between the values of torque for the angle. An overall value of friction was determined by taking the average of sample values taken from the two runs. The resulting value of this process is a value of 693 lb-in (78.3 N m).

On comparisons of this value with those used in the previous studies simulations, it is seen that this value is in relatively good agreement with the NCHRP study value of 600 lb-in (67.8 N m). It also shows that the FHWA study value of 5,000 lb-in is excessive for this vehicle. Consequently, the values of steering inertia and friction indicated in table 13 are believed to be reasonable for describing the vehicle is question.

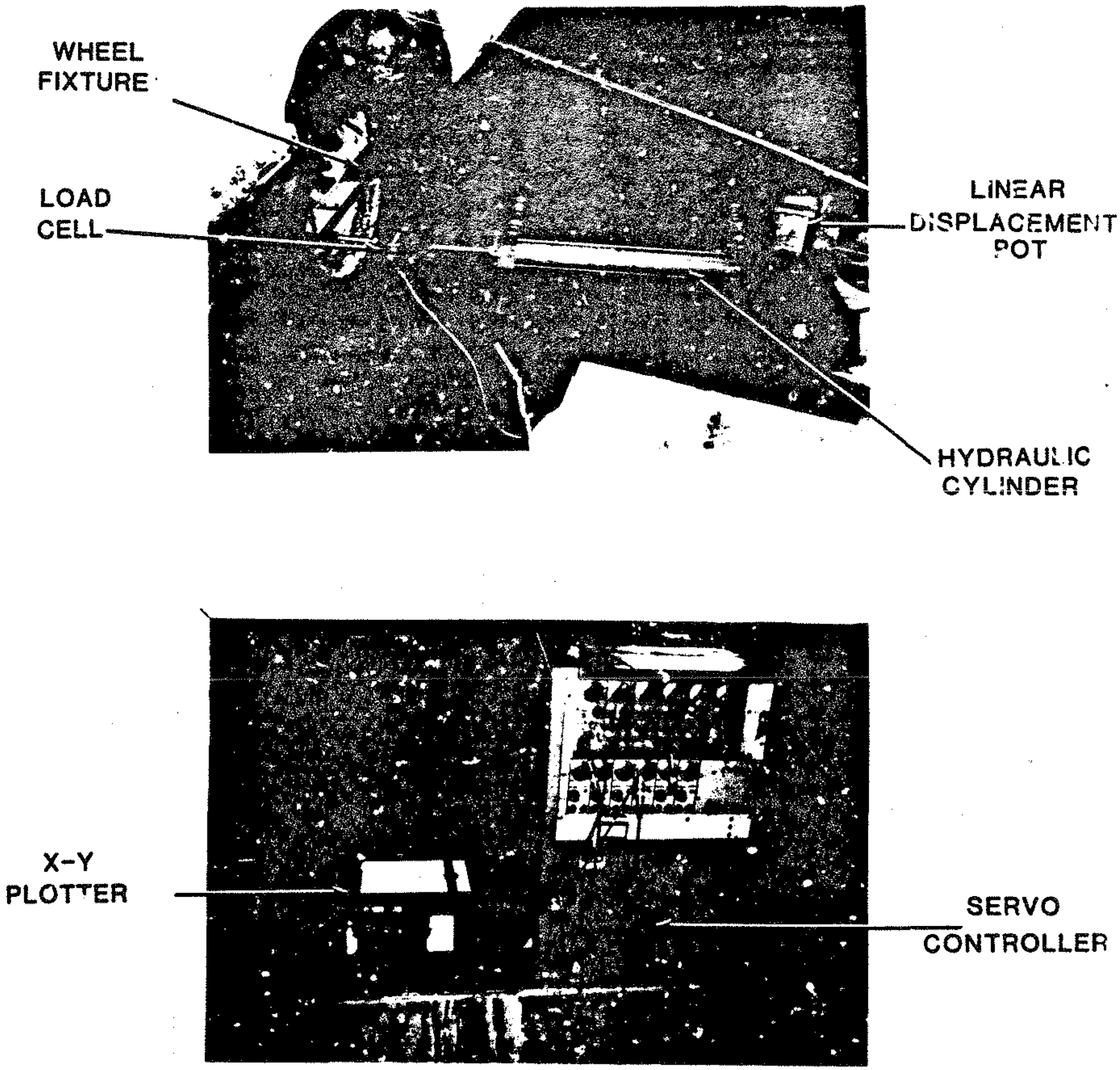


Figure 19 EXPERIMENTAL SET-UP FOR MEASURING THE STEERING FRICTION TORQUE

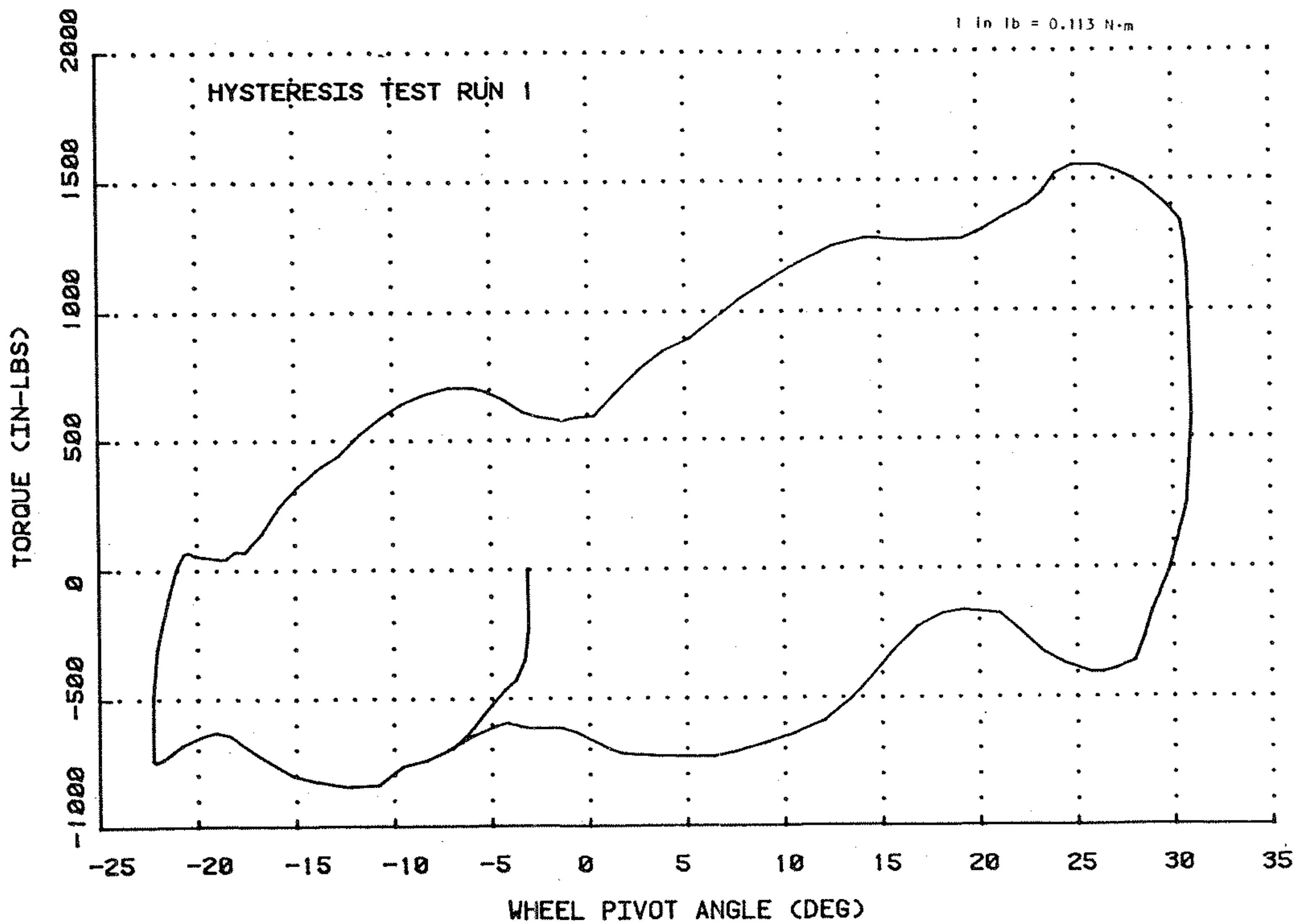


Figure TORQUE VS. WHEEL ANGLE FOR HYSTERESIS TEST RUN 1

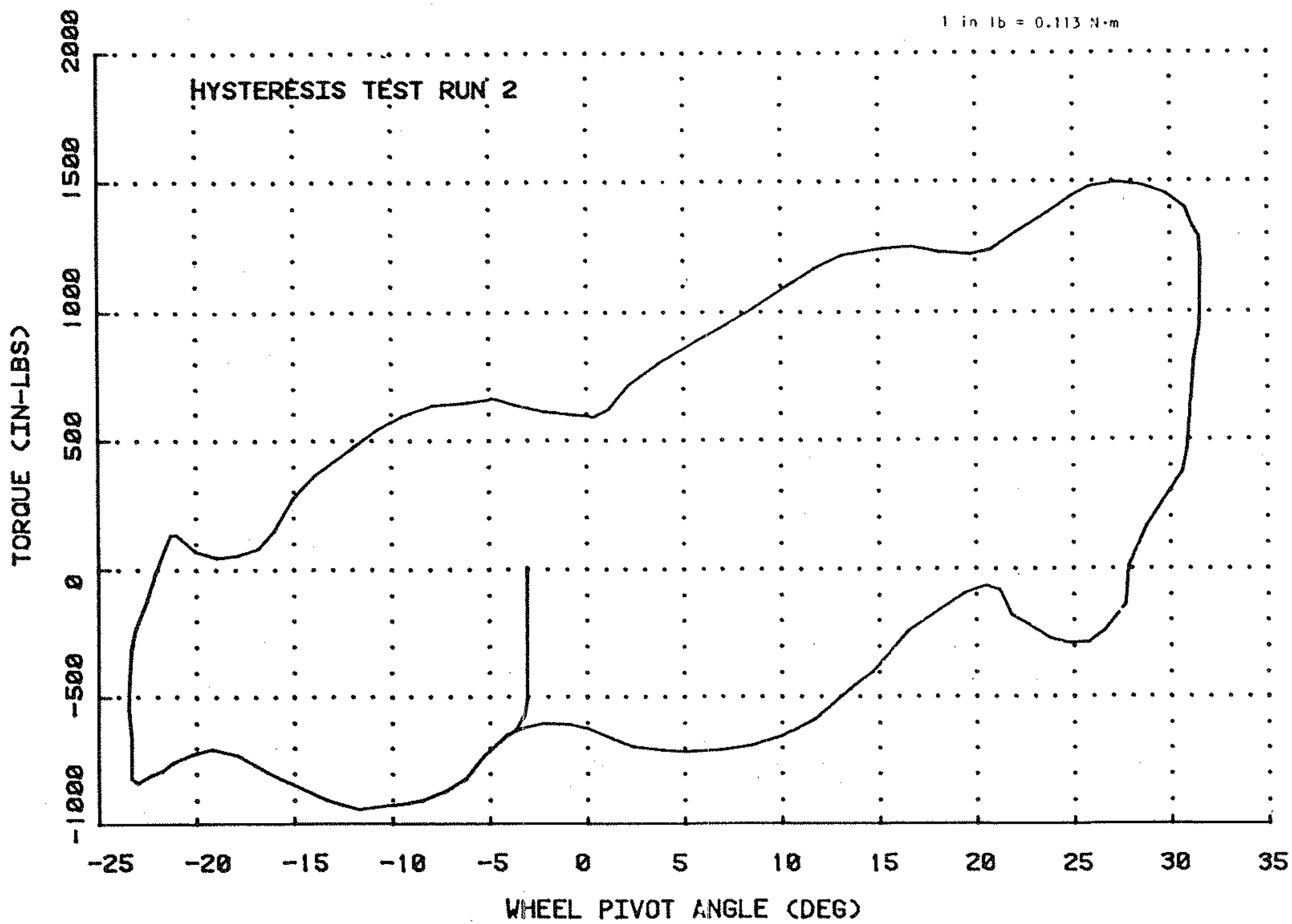


Figure 21 TORQUE VS. WHEEL ANGLE FOR HYSTERESIS TEST RUN 2

The remaining data needed for the simulation are shown in tables 16 and 17. Generally the tire data, as indicated in table 16 identical for all studies. A potentially significant data item is that of T, the tire deflection at which bottoming in vertical response when traversing a curb, as was noted in section 3.3. The basis for using either value of 3 or 6 inches (76.2 or 152.4 mm) is not firm nor is the rate multiplier of 10 used to represent bottoming as no data on tire rates at extreme deflection are known. Hence, the use of 3 inches for JT in the best data set is arbitrary but appears reasonable.

Sources of the remaining HVOSM data are indicated in table 17. As is indicated, track change data, antipitch data, and drag force data were not used in the final data set as the appropriate values for the vehicle in question are not available, and they were not expected to influence results to a strong degree.

Table 16

TIRE DATA

Variable	Units	"Best" Data Set
RWHJE	(in)	8
DRWHJ	(in)	0.25
KT	(lb/in)	1300
T	(in)	3
T		10
A_0		4000
A1		8.4
A_2		3000
A3		1.71
A_4		4200
T		1.0
		0.8
RW	(in)	14.68

1 in = 25.4 mm
1 lb/in = 17.86 kg/m

Table 17

OTHER HVOSM DATA

Variable	FHWA Report	NCHRP Report Validation Study	"BEST"
Camber data	Ref. 3	unknown	Ref. 3
Track change data	unknown	not applicable	unknown
Antipitch data	Ref. 7	unknown	not used
Control tables	drag force	unknown	not used

4. CURB IMPACT SIMULATION RESULTS

The following section covers the comparisons of the results from the computer simulations made by MGA and the corresponding full scale tests. These comparisons only involve the simulations made with data deemed as the most appropriate, or the best for the vehicle being simulated. The full-scale tests involved are those conducted on the type C and E curbs in the NCHRP study in Ref. 3 and the tests conducted on the type X curb by Southwest Research Institute in Ref. 8.

4.1 Comparison of Simulation and Test Results for Type C and E Curbs

In order to determine how well the "best" data set corresponds to the full scale test results reported in the NCHRP Report 150, all 18 impact conditions were simulated using the "best" data set. Table 18 briefly compares the available tabulated data from the full-scale tests to the corresponding data from the best data set simulations. Using the same criterion for agreement (up to 10 percent difference in values allowed), this table shows that the best data simulation did a better job simulating the type E curb impacts than the type C impacts.

As a means of further comparisons, the results of the "best" data simulations have been overplotted onto the plots presented by NCHRP in their validation efforts. (The full set of plots are shown in appendix D.)

The graphical results again support that the data used in representing the 1963 Ford Galaxie (the best data set) affords a better correlation between the type E curb impacts and the full-scale tests than between the type C curb impacts and the full-scale tests. This is easily seen by glancing through the plots of figures 96 through 113 (appendix D). The majority of the runs involving the type C curb show that the HVOSM predicts vehicle redirection - some even to the point of the vehicle completely

Table 18

FULL SCALE AND "BEST" DATA SIMULATION TABULAR RESULTS COMPARISONS

			Full Scale Test Results		"Best" Data Simulation Results	
Test #	Actual Approach Speed (mph)	Actual Approach Angle (Deg)	Max Bumper Rise Above Curb (in)	Max Peak Vert. Accel. (G)	Max Bumper Rise Above Curb (in)	Max Peak Vert. Accel. G (upward)
Curb Type E:						
N-2	30.4	5.1	24.1	-	21.3	0.22
N-3	45.6	5.0	24.3	-	23.1	0.58
N-4	59.3	4.6	23.9	2.0	23.7	0.79
N-5	32.0	11.6	20.8	1.0	21.9	1.08
N-6	45.3	11.1	23.7	2.0	23.3	1.68
N-7	63.6	12.6	23.5	4.0	26.4	4.48
N-8	32.7	18.5	23.5	1.8	21.9	3.07
N-9	41.6	18.7	21.9	3.0	23.8	2.46
N-10	63.0	17.6	23.3	3.6	27.3	3.20
Curb Type C:						
N-11	34.2	4.9	26.2	1.0	11.4	1.97
N-12	44.7	5.1	24.8	1.0	11.5	1.13
N-13	34.2	11.2	23.8	1.8	24.2	1.74
N-14	43.5	12.8	23.1	2.6	23.0	3.18
N-15	32.1	17.4	22.1	2.4	21.6	2.22
N-16	43.0	18.4	23.5	4.6	24.9	7.82
N-17	66.5	5.1	24.3	1.2	11.6	2.85
N-18	62.2	12.3	21.4	4.2	27.8	7.47
N-19	61.5	18.6	23.0	4.0	26.7	7.64

Multiply in by 25.4 to obtain mm
Multiply mph by 1.609 to obtain km/h

returning to the roadway side of the curb. (An example of this major redirection is shown in figure 22.) In the three cases where the HVOSM prediction agrees with the test results in saying that the vehicle continues beyond the curb (tests N-16, N-18, and N-19), there is a relatively poor agreement in the bumper height, roll angle, and pitch angle responses. Figure 23 shows that for both the N-16 and N-18 simulations that HVOSM response predictions changed more quickly and gave greater value ranges than those seen in the full-scale tests. The greater value ranges are also seen in the response plot for the N-19 simulation but there is a better agreement in the general patterns of the responses.

As stated above, the type E curb impact simulations did come closer to the test results than did the type C curb impact simulations. In general, as the encroachment conditions for the type E curb impact simulation moved from the low-speed/low-angle case toward the high-speed/high-angle case, the differences between the simulation and test results became larger. This is especially noticeable as the encroachment angle increases. This follows the observation made from the NCHRP duplication results. The results again show that the data works best when simulating the low (and moderate) impact speed and angle conditions. Another general observation is that the HVOSM predicts greater vehicle redirection than actually observed in the full-scale tests.

Besides the general characteristics seen in the series of plots for the type E curb impacts, the individual responses also followed trends. Figure 24 shows the trend seen in the vehicle trajectory. The trend is that as the encroachment angle increases, there is a greater divergence from the test results by the simulation results. The trend seen in the roll and pitch angle response follows the same general pattern. That is, as the encroachment speed and angle increases, the roll and pitch responses from the simulation deviate further from the test results. Figure 25 shows this by showing the roll angle response for the extreme speed/angle cases. The pitch angle response also follows this trend but, because of the smaller range of values, is harder to see.

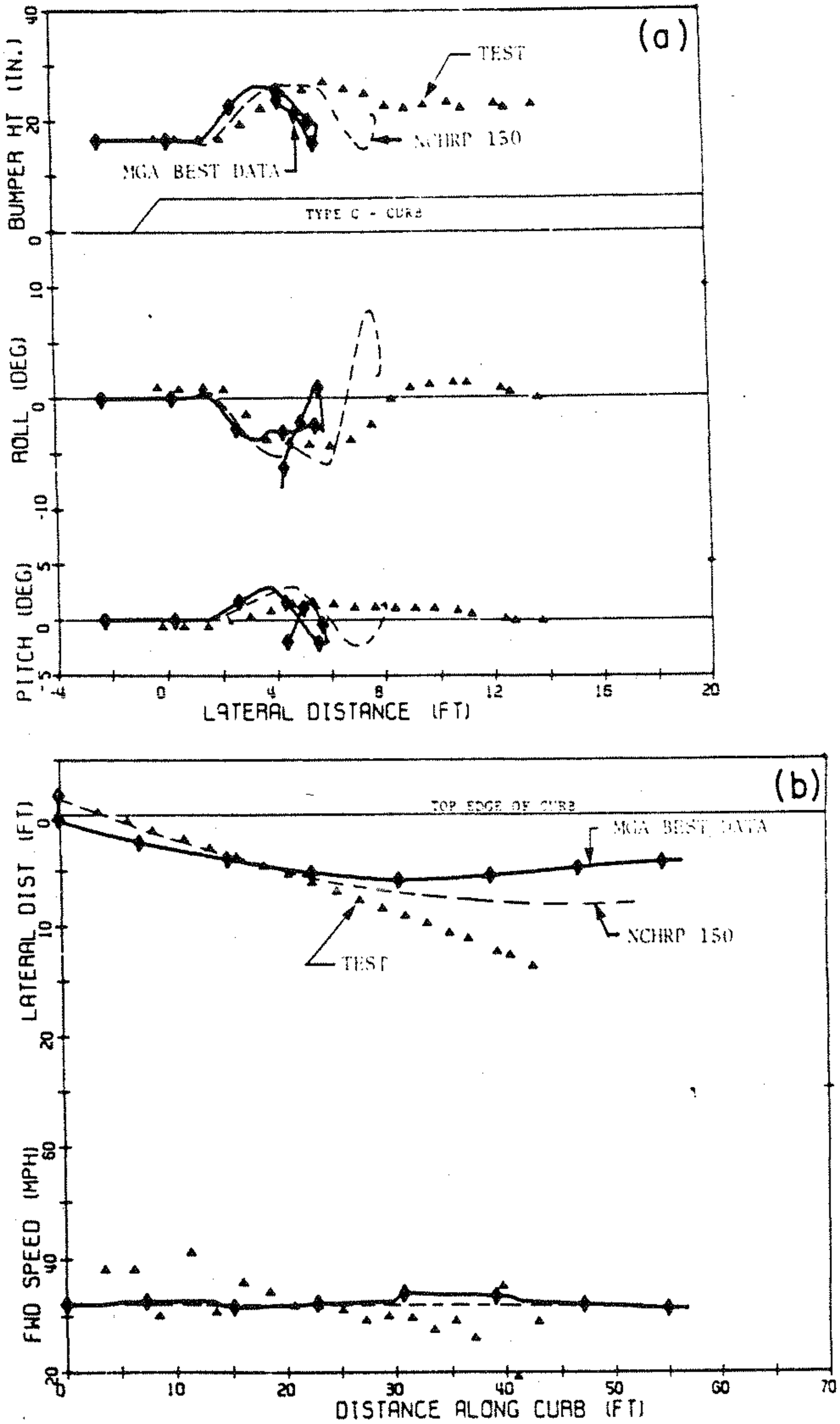
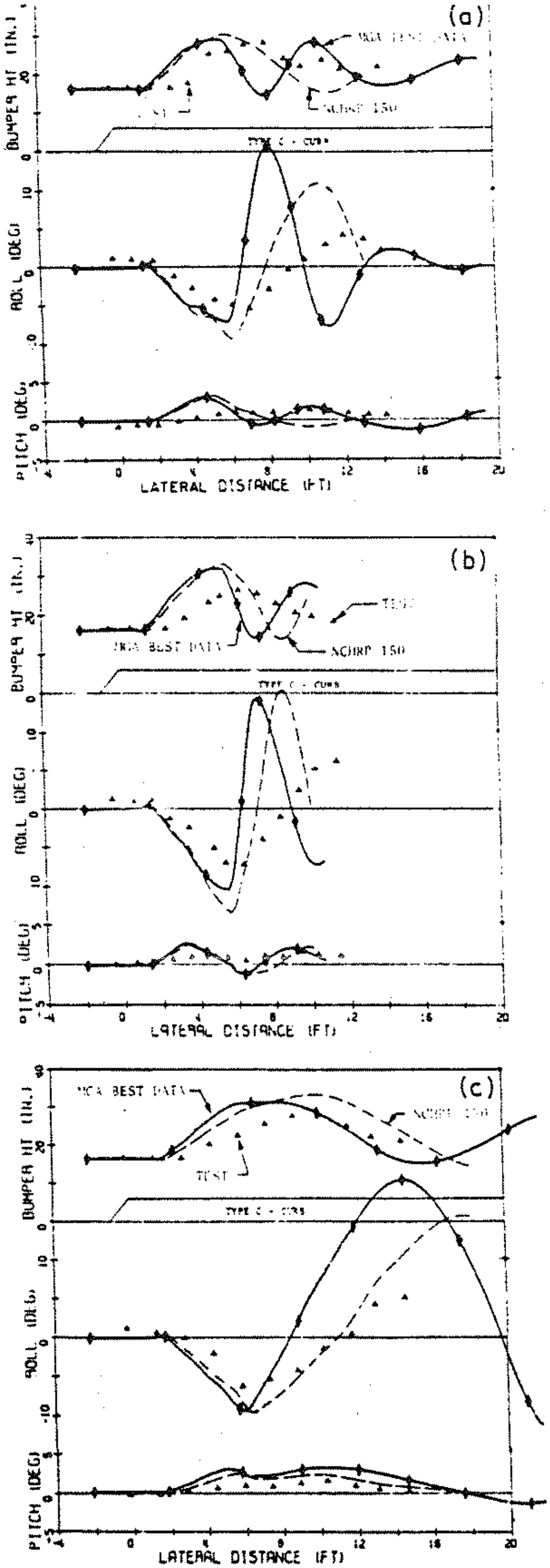


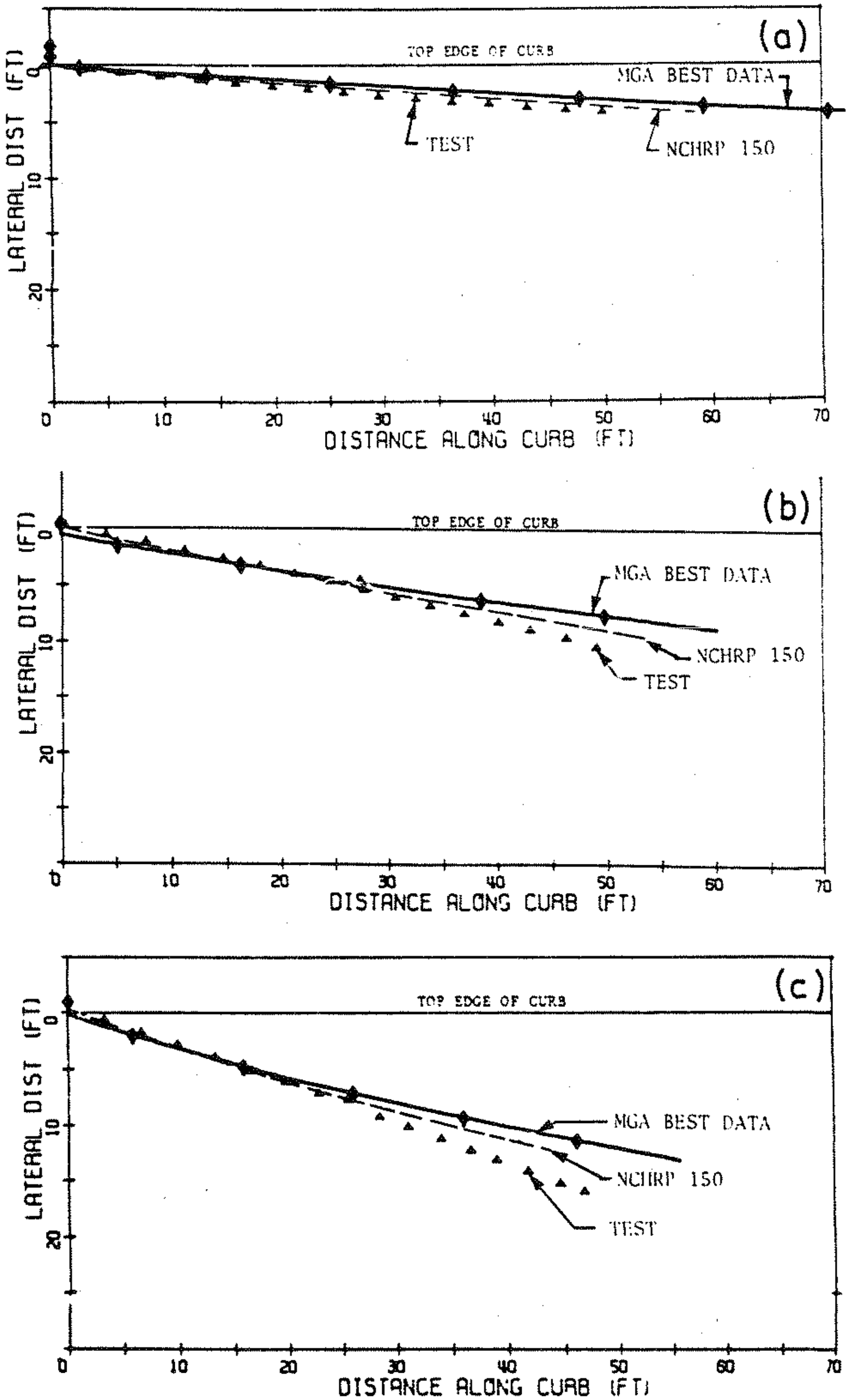
Figure 22 "BEST" DATA SET RUN N-15 30 MPH AND 20 DEG IMPACTS: (A) VEHICLE ROLL PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h



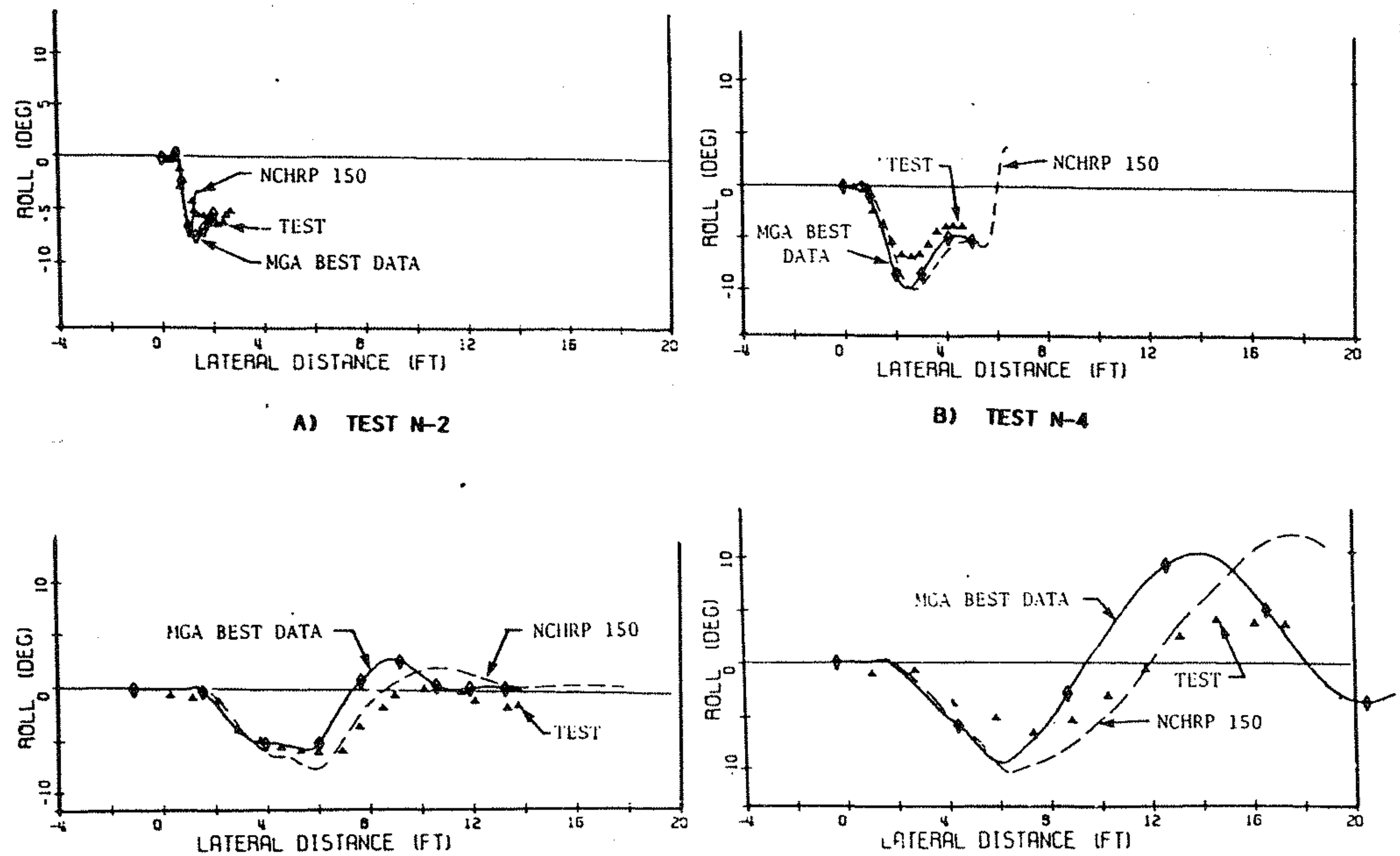
1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 23 BUMPER HEIGHT, ROLL, & PITCH RESPONSES FROM THE "BEST" DATA SET FOR TESTS N-16, N-18, & N-19



1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 24 VEHICLE PATH RESPONSES FROM THE "BEST" DATA SET FOR TESTS N-3, N-6, & N-9



A) TEST N-2

B) TEST N-4

C) TEST N-8

D) TEST N-10

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

Figure 25 ROLL ANGLE RESPONSES RESULTING FROM THE USE OF THE "BEST" DATA SET FOR THE EXTREME SPEED/ANGLE TESTS FOR THE TYPE E CURB

As a reference to the original simulation efforts the plots in appendix D also show the results of the HCHRP report. In general, the results from using the best data set for the type C curb impacts gave poorer correlation with the test results than did the NCHRP simulations. A general overview of Appendix D shows that in some cases the best data simulations are better than the NCHRP simulations and in some they are worse, and in some cases there is a good agreement. A good example of this is seen when viewing the bumper height responses. Although the best data closely follows the data set used for duplications of the NCHRP simulations, it should be kept in mind that the actual data used in NCHRP study was not available and the best approximation of that data had to be used. This uncertainty of original data is a potential cause for the sometimes large differences in results.

The fact that the data was able to simulate the impacts of one curb type (type E) fairly well and the other curb type (type C) quite poorly indicates that the curb itself (its physical characteristics) and its interaction with the tire may play an important part in the simulation process.

4.2 Comparison of Simulation and Test Results for Type X Curb

In the NCHRP Report 150, conclusions had been drawn on the redirection capabilities of type X curbs through exercising the HVOSM. The type X curb is the lower section of the New Jersey Safety Shape and had not been subjected to full-scale vehicle tests at the time of the report. Consequently, no correlation between simulation and test results was available at that time. In the interim, a full-scale crash test has been conducted on the type X curb (Ref. 8). Thus, the opportunity is now available to correlate HVOSM predictions againt test results for this curb.

To validate the HVOSM's applicability for simulating type X curb impacts, the data had to be established for the vehicle used in the full-scale tests. The vehicle used was a 1969 Plymouth Fury weighing 4,340 lb (1.97 Mg).

The remaining data necessary for the simulation was not readily available. A search of known literature was conducted in an attempt to uncover the necessary data. This search, however, produced very little additional data. The only additional data that was found consisted of wheel base, front and rear track, and weight distribution from Ref. 9. Effort was therefore placed on obtaining the necessary data by deriving the values from typical vehicle information. The derivation of these values involved the use of the equations presented in the HVOSM User Manual (Ref. 10). The values which could not be calculated from the given equations were taken from available data of other (similar) vehicles. Table 19 gives a general outline of the sources of the various data categories. From this table, it becomes apparent that most of the data had to be taken from sources not directly concerned with a 1969 Plymouth Fury. The results of this vehicle data compilation are shown in table 20. This table shows the data in its form ready for direct use by the HVOSM program.

Upon completion of the simulation run using the inputs shown in table 4-3, the results were checked against the full-scale test results presented in Reference 8. The simulation results showed poor correlation with the test results. The most evident discrepancy between the two sets of results was the difference in vehicle trajectories. In the test, the vehicle mounted the curb (figure 26); whereas, the simulation results indicated the vehicle redirecting before the tires climbed the height of the curb (figure 27).

In an attempt to better understand the reason for this poor correlation, a limited sensitivity study was conducted. The purpose of this sensitivity study was to see if some of the input data might be the cause for the differences in the two sets of results. The parameters singled out for this study were tire bottoming deflection, yaw inertia, and the curb friction. In all three changes, none were able to change the fact that the simulation predicted redirection, as is seen in the yaw angle plots in figure 28. In the

Table 19

DATA SOURCES FOR DATA USED IN THE TYPE X CURB VALIDATION RUN

Inertial Data	Calculated from "typical values" equations[1]
Dimensional Data	All inputs except those for [2] and the sprung mass CG height calculated from "typical values" equations[1] and sprung mass CG height taken from data for a similar vehicle[3]
Suspension Data	All inputs except the linear suspension load deflection rates (front and rear) and the viscous damping coefficients (front and rear) taken from data for a similar vehicle[3] linear suspension load deflection rates and viscous damping coefficients calculated from "typical values" equations[1]
Steering Data	Taken from data for a similar vehicle[3]
Tire Data	Taken from data for a similar vehicle[3]
Camber Data	Taken from data for a similar vehicle[3]
Track Change Data	Taken from data for a similar vehicle[3]
Antipitch Data	Taken from data for a similar vehicle[3]

1 "Typical values" equations are presented in the HHOSM User's Manual (Ref. 10)

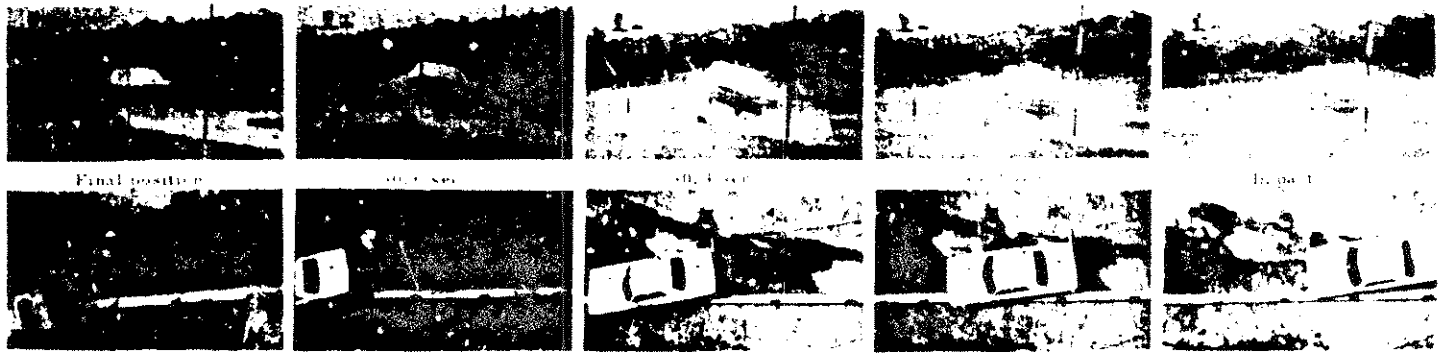
2 ρ is the distance between the rear axle CG and the rear roll center

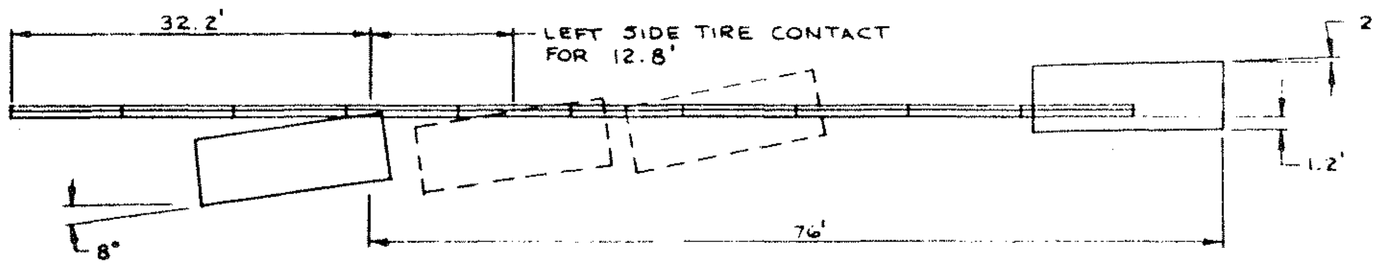
3 Data for 1963 Ford Galaxie as documented in the report prepared for the Federal Highway Admin. entitled "Follow-up HVOSM Studies of Highway Curb Impacts"

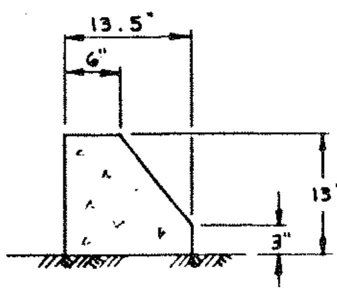
Table 20

HVOSM INPUTS FOR TYPE X CURB VALIDATION RUN

```
INPUTS FOR HVOSM VALIDATION RUN FOR CURB TYPE X                                            0 100
0.0       1.0       .005      .010      70.0      30.0      .08       1.0                  0 101
0                   1         5.001                                                        0 102
          1                                                                                0 103
          1         1         1         1         1         1         1                    0 104
  DEFINITION OF TEST VEHICLE                                                               0 200
9.658     0.606     0.963     4445.     27127.    31955.    -192.     472.0                0 201
50.50     69.50     62.85     62.57     -2.0      43.92                                    0 202
54.55     0.0       0.0       -64.45    0.0       0.0                                      0 203
106.0     300.0     600.0     300.0     600.0     0.500     -3.0      5.0                  0 204
117.0     300.0     600.0     300.0     600.0     0.500     -4.0      4.5                  0 205
7.87      58.0      0.001     13.98     97.0      0.001                                    0 206
266000. 59244.0 0.059                                                                      0 207
300.0     5000.0    0.523     100000. 0.050       1.50                                     0 208
-5.0      5.0       1.0       1.0                                                          0 209
-5.7      -3.90     -2.45     -1.30     -0.40     0.30      0.60      0.65      0.30       1 209
-0.40     -1.30                                                                            2 209
-1.22     -0.78     -0.46     -0.21     -0.06     0.07      0.08      0.04      -0.08      3 209
-0.34     -0.69                                                                            4 209
-5.0      5.0       0.50                                                                   0 210
0.1079    0.1053    0.1030    0.1011    0.0994    0.0981    0.0971    0.0964    0.0959     1 210
0.0958    0.0960    0.0965    0.0973    0.0984    0.0998    0.1015    0.1035    0.1058     2 210
0.1085    0.1114    0.1147                                                                 3 210
-5.0      5.0       5.0                                                                    0 211
0.092     0.092     0.092                                                                  1 211
                        SEARS SUPER TREAD                                                  0 300
1.0       1.0       1.0       1.0       8.0       0.25                                     0 301
1300.     6.0       10.0      4000.     8.4       3000.     1.710     4200.0    1.0        1 301
0.80                                    14.68                                              0 302
DRIVELINE,AERODYNAMICS,FRICTION                                                            0 400
0.0       0.30      0.10      0.0       1.0       1.0                                      0 401
-105.     -105.     -105.     -105.                                                        1 401
-315.     -315.     -315.     -315.                                                        2 401
 TYPE X CURB                                                                               0 500
150.0     150.005 157.005 163.005 165.295                   1.0                            0 507
-3.0      -13.00    -13.00    0.0                                                          0 508
-89.9     -55.00      0.0       80.0      0.0                                              0 509
35.0 MPH, 8.1 DEG                                                                          0 600
0.0       0.0         8.1     0.0       0.0       0.0       0.0       0.0                  0 601
0.0        80.0     -24.14    616.14    0.0       0.0                                      0 602
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0                  0 603
                                                                                           09999
```







"X" Barrier Cross Section

Test No.	TB-6
Date	5/27/77
Drawing	AASHTO Type "X"
Barrier Section	13 in. (0.3m) x 13.5 in. (0.3m) x 10 ft (3m) concrete
Length of Installation	100 ft (30m)
Ground Conditions	Dry
Barrier Deflection	
Max. Dynamic	1.2 ft (0.4m)
Max. Permanent	1.2 ft (0.4m)

Vehicle	1969 Plymouth Fury
Vehicle Mass (w/instrumentation)	4340 lb (1970kg)
Impact Speed	35.0 mph (56.3km/hr)
Impact Angle	8.1 deg
Exit Angle	2 deg
Vehicle Acceleration (max 50 ms avg)	
Lateral	-1.08g
Longitudinal	-2.03g
Resultant	2.08g
Vehicle Rebound Distance	1.2 ft (0.4m)
Vehicle Damage	
TAD	11-LD-1
VDI	11ULXN9

Figure 26 SUMMARY OF RESULTS, TESTS CONDUCTED BY SOUTHWEST RESEARCH INSTITUTE

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

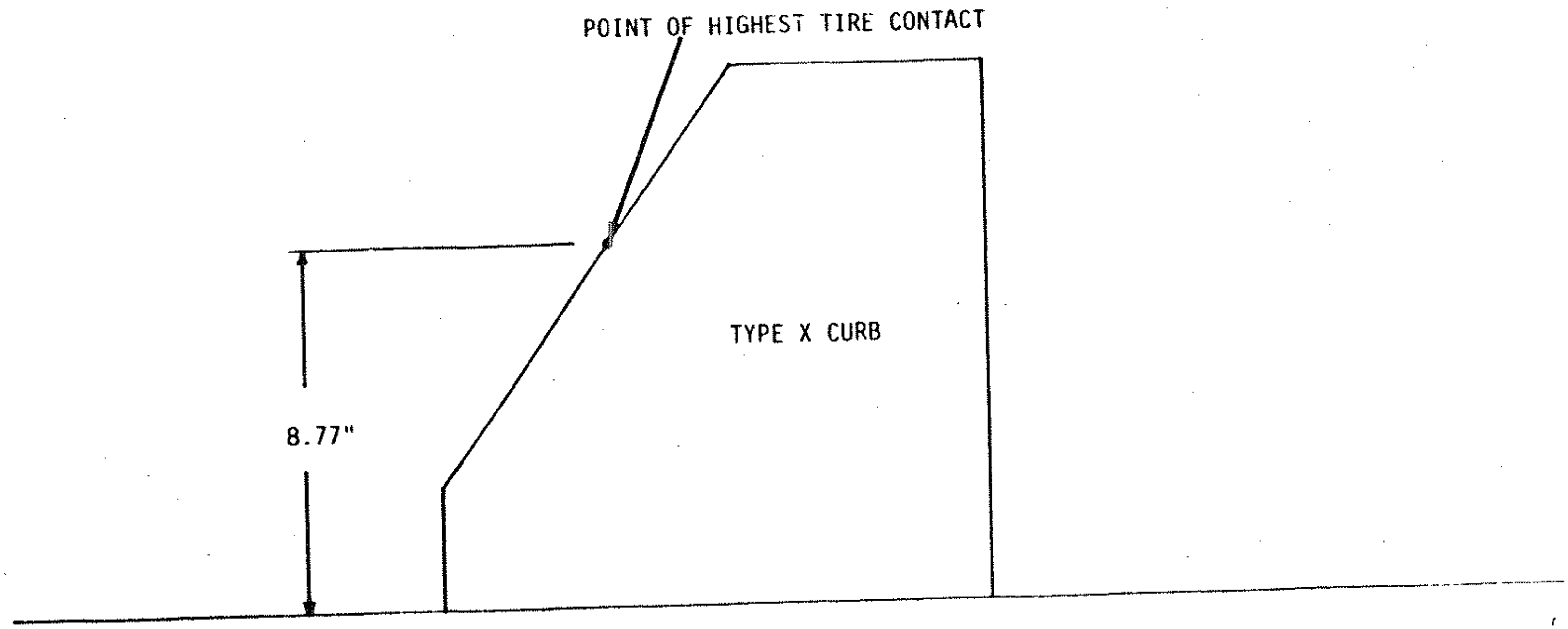
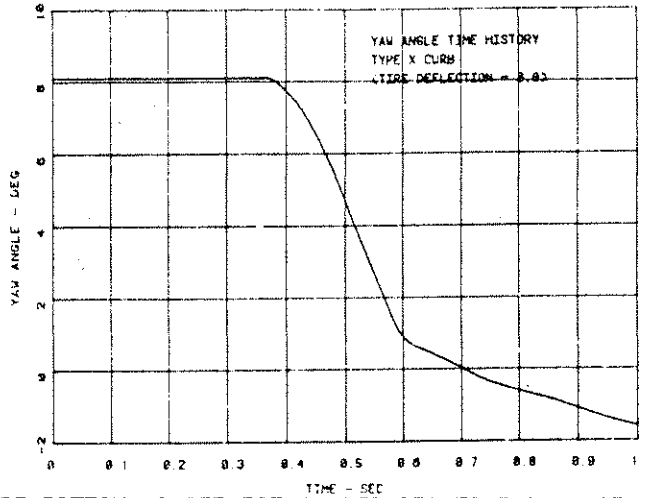
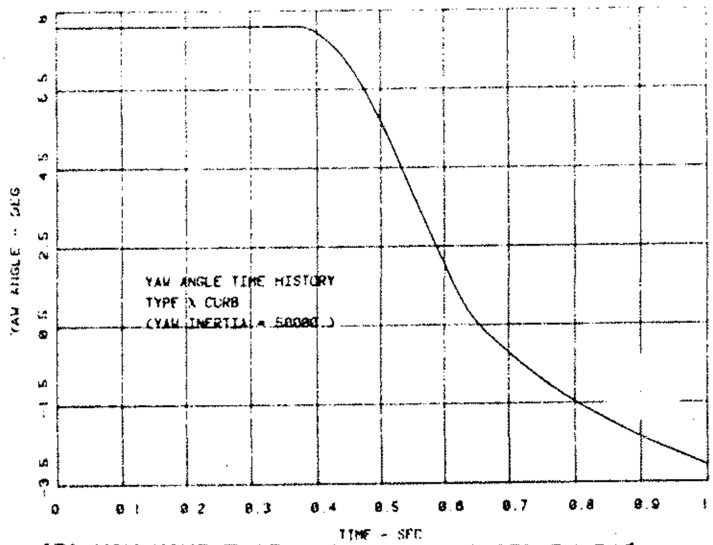


Figure 27 MAXIMUM TIRE CONTACT RISE POINT FOR TYPE X CURB VALIDATION RUN

1 in = 25.4 mm

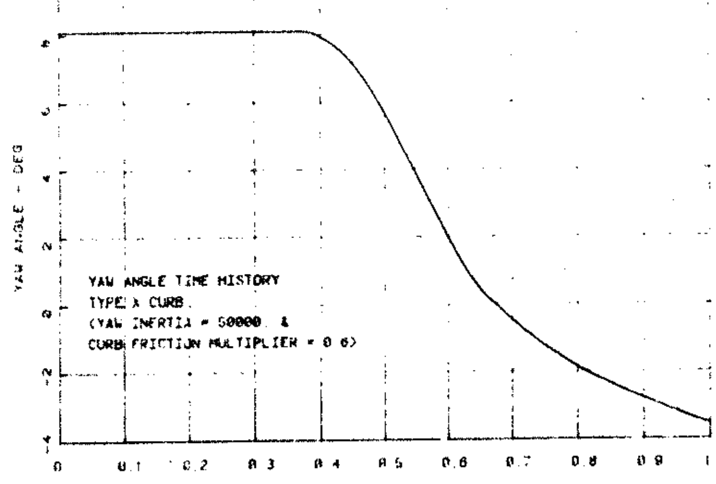


(A) TIRE BOTTOMING DEFLECTION REDUCED TO 3.0 IN (76 MM)



(B) YAW MOMENT OF INERTIA INCREASED BY 36%

Figure 28



(C) YAW INERTIA INCREASED AND CURB FRICTION DECREASED

Figure 4 TYPE X CURB YAW RESPONSE

first change, the tire bottoming deflection was changed from 6.0 inches (152.4 mm) inches to 3.0 inches (76.2 mm). This change actually increased the redirection tendency by causing the vehicle not to ride up as high onto the curb. (The maximum tire contact point evaluation for this first sensitivity run was 8.27 inches (222.8 mm) - 0.5 inches (13 mm) less than the initial run.) The second change was an increase of 36 percent in the yaw moment of inertia. This increase did allow the vehicle to ride further up the curb to a maximum tire contact point elevation of 9.92 inches(252.0 mm), but still did not allow the vehicle to mount the curb. The third change was actually an addition to the second change. In this change the yaw inertia was kept at the increased level while the curb friction multiplier was decreased by 40 percent. This combination also caused the vehicle to rise further up the curb to a maximum tire contact point elevation of 9.88 inches (25.0 mm); but again, redirection occurred.

Since all efforts failed to bring about an agreement between the two sets of results, efforts were directed toward comparisons of HVOSM results with previously reported validation efforts. This effort involved a 1972 Ford Galaxie impacting a New Jersey Safety Shape (also known as a New Jersey Barrier). In this case the results of the simulation were compared against the results given in Ref. 11. The input data deck used for this comparison was used as reported with modifications to reflect the current version of the program. Table 21 shows this data deck in its form ready for use by the HVOSM program.

Upon completion of this validation run for the New Jersey Barrier, the results were checked against those of the physical test. Figure 27 shows the comparisons between the simulation (HVOSM) and experimental (full scale) results for the vehicle roll angle and yaw angle time histories. Both of these comparisons show that the HVOSM simulation vehicle does not respond to the same degree as the full-scale test vehicle. A further example of the HVOSM predicting values lower than the experimental values is that the HVOSM predicted the maximum tire contact point elevation to be 14.11 inches (358.4

Table 21

HVOSM INPUTS FOR 1972 FORD GALAXIE/NEW JERSEY BARRIER RUN

```
 INPUTS FOR 1972 FORD GALAXIE WITH N.J. BARRIER                                   0 100
0.0     1.0     .005     .010     70.0     0.0     0.0                            0 101
0               1        4.0005                                                   0 102
       1                                                                          0 103
       1        1        1        1        1       1        1                     0 104
VEHICLE DEFINED IN REPORT # FHWA-RD-77-4                                          0 200
9.192   0.608   0.991    5209.    55500.   50000.  -192.    600.0                 0 201
49.80   71.20   64.0     65.5     -2.0     46.5                                   0 202
0.0     9.0     8.0      0.0      -9.0     8.0                                    0 203
131.0   300.0   600.0    300.0    600.0    0.500   -3.0     3.0                   0 204
192.0   300.0   600.0    300.0    600.0    0.500   -4.0     4.0                   0 205
3.5     55.0    0.001    3.9      50.0     0.001                                  0 206
266000. 61900.0 0.070                                                             0 207
492.0    600.0  0.4         5000. 0.075    1.50                                   0 208
-5.0     5.0     1.0     1.0                                                      0 209
-5.7    -3.90   -2.45    -1.30    -0.40    0.30    0.60     0.65     0.30         1 209
-0.40   -1.30                                                                     2 209
-1.22   -0.78   -0.46    -0.21    -0.06    0.07    0.08     0.04     -0.08        3 209
-0.34   -0.69                                                                     4 209
-10.0   10.0    5.0                                                               0 210
0.0     0.0     0.0      0.0      0.0                                             1 210
-10.    10.     5.0                                                               0 211
0.0     0.0     0.0      0.0      0.0                                             1 211
                    TIRE DATA                                                     0 300
1.0     1.0     1.0      1.0      6.0      0.25                                   0 301
1098.   3.0     10.0     4400.    8.276    2900.   1.780    3900.0   1.0          1 301
0.80                              15.0                                            0 302
 NEW JERSEY BARRIER                                                               0 500
121.0   121.005 128.005 130.005                    0.625                          0 507
-3.00   -13.0   -32.0                                                             0 508
-89.9   -55.0   -83.951  0.0                                                      0 509
60.3 MPH, 7.4 DEG                                                                 0 600
0.0     0.0     7.4      0.0      0.0      0.0     0.0                            0 601
0.0      76.0   -25.138 1061.0    0.0      0.0                                    0 602
0.0     0.0     0.0      0.0      0.0      0.0     0.0      0.0                   0 603
                                                                                  09999
```

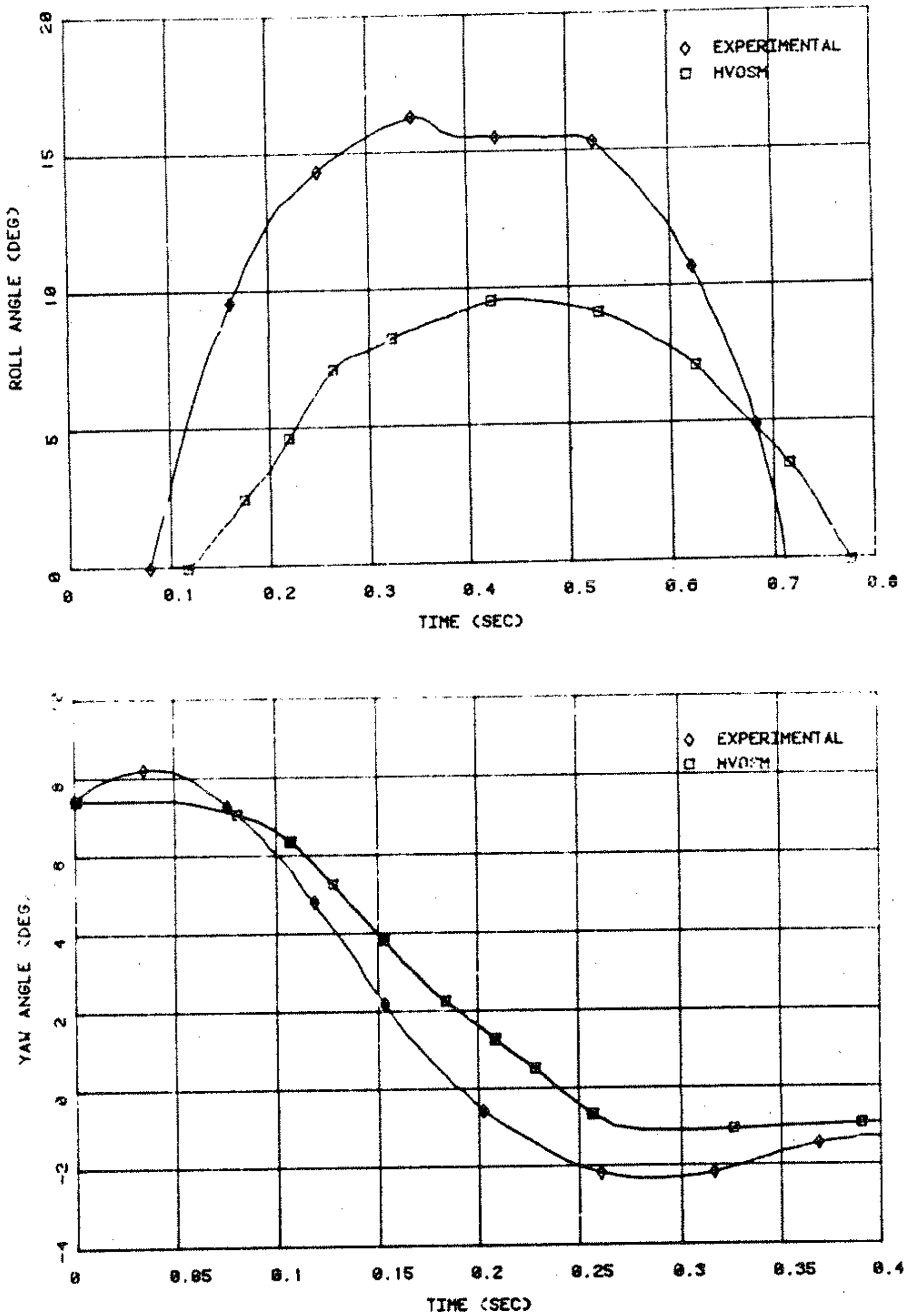


Figure 29 COMPARISON OF EXPERIMENTAL (FULL SCALE) AND HVOSM ROLL ANGLE & PITCH ANGLE TIME HISTORIES

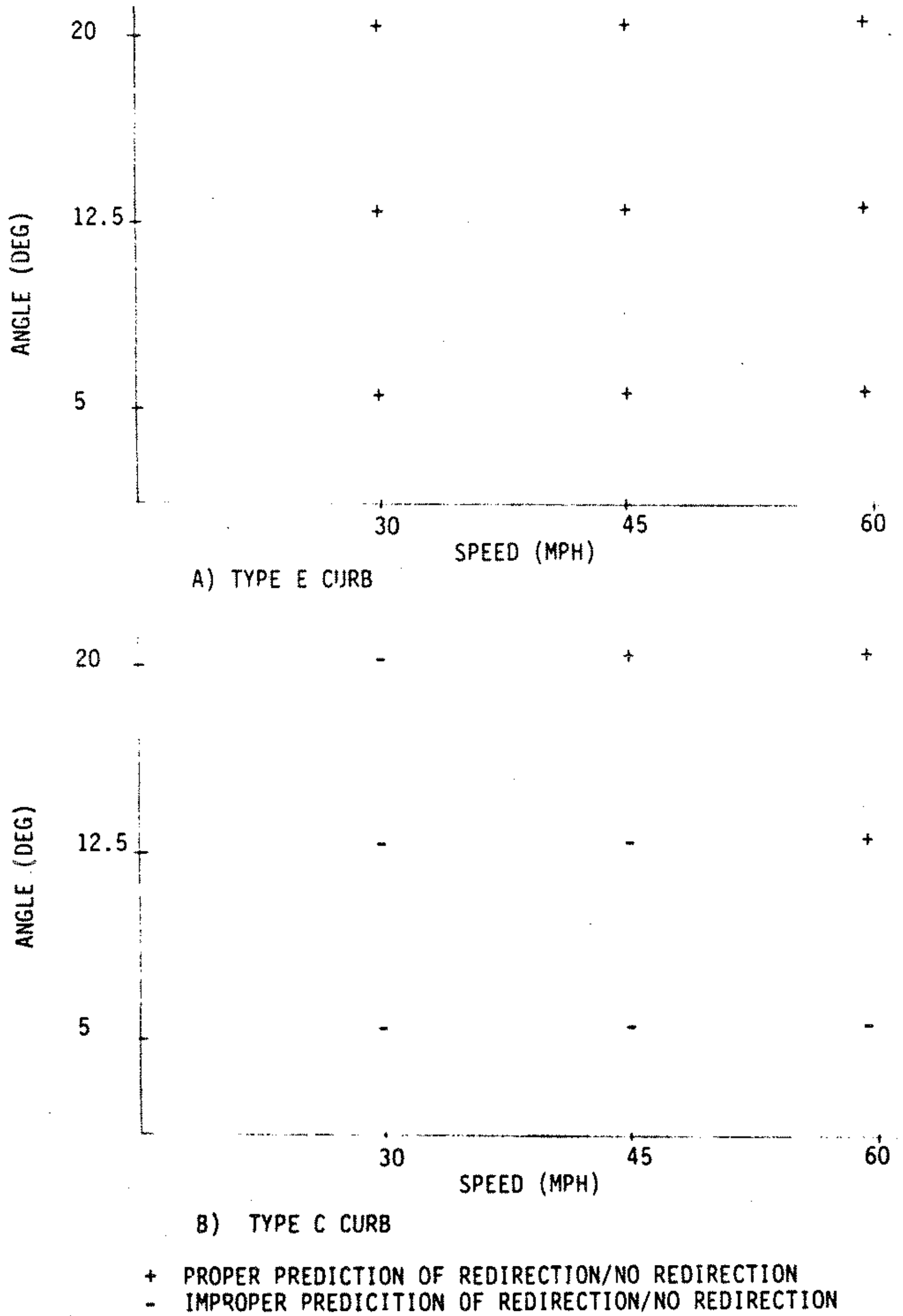
mm) above the barrier, while the actual (test) value was approximately 23.25 inches (591 mm) above the base of the barrier. Thus, the current version of the HVOSM consistently predicts lower tire elevations than are observed in tests.

5. DISCUSSION

The overall results of the comparison of the HVOSM responses using the final vehicle data to curb traversals to corresponding test results is disucssed in this section. Figures 30, 31, and 32 present a subjective evaluation of comparisons of trajectory response bumper height response, and roll and pitch angle response of simulation results and full-scale test results. These evaluations are based on visual comparison of the data plots presented in appendix D for the entire event and are thus subjective in nature. However, they do lead to insight into the ability of the HVOSM to properly predict vehicle response to curb impacts.

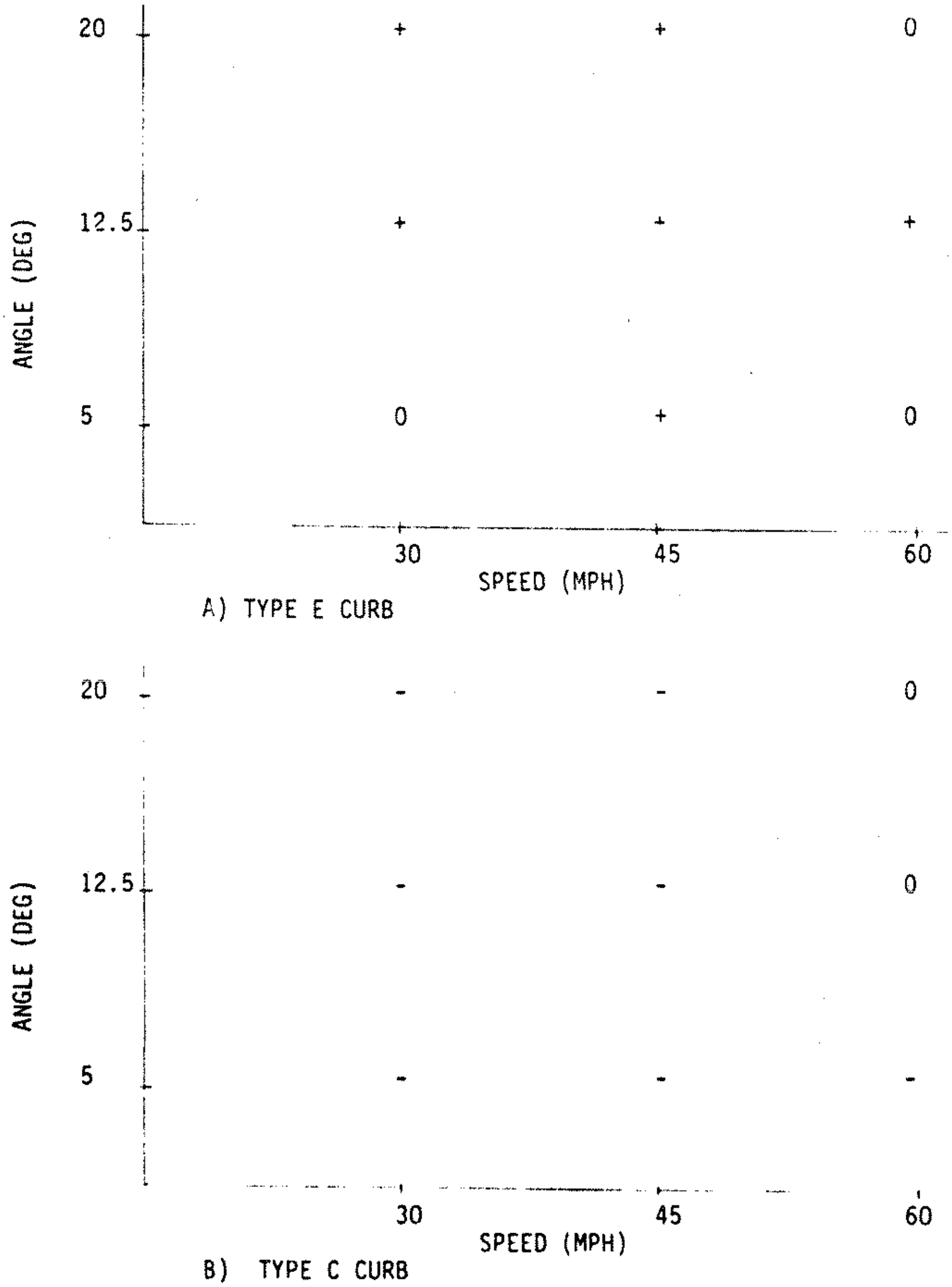
An evaluation of the trajectory response is shown in figure 30. This evaluation is based on the proper or improper prediction of vehicle redirection only. That is, proper redirection/no redirection is indicated if the final heading angle of the simulated vehicle is in agreement with that of the test vehicle. In some cases where agreement occurs, deviations in trajectory are apparent; however, the final heading angles nonetheless agree. As can be seen in the figure, agreement occurs for all combinations of speed and approach angle for the type E curbs. However, agreement occurs only for high speed/high-angle cases for the type C curb. In the cases where disagreement occurs for the type C curb, the simulation predicted redirection of the vehicle while the vehicle did not redirect in the tests. This general result indicates that the interaction between the tire and curb for the type C curb resulted in more steering response in the simulation than occurred in the test vehicle, hence, the greater likelihood of steering away from the curb.

Evaluations of bumper height responses are shown in figure 31. In this case, all simulated responses to the type E curb are judged to be either fair or good in comparison with the test responses. However, only at 60 mph (97 km/h) at the two higher approach angles was the simulated bumper height response judged to be in fair agreement with the test responses. In all other



1 mph = 1.609 km/h

Figure 30 TRAJECTORY RESPONSE EVALUATION



+ GOOD CORRELATION WITH TEST RESULTS
O FAIR CORRELATION WITH TEST RESULTS
- POOR CORRELATION WITH TEST RESULTS

1 mph = 1.609 km/h

Figure 31 BUMPER HEIGHT RESPONSE EVALUATION

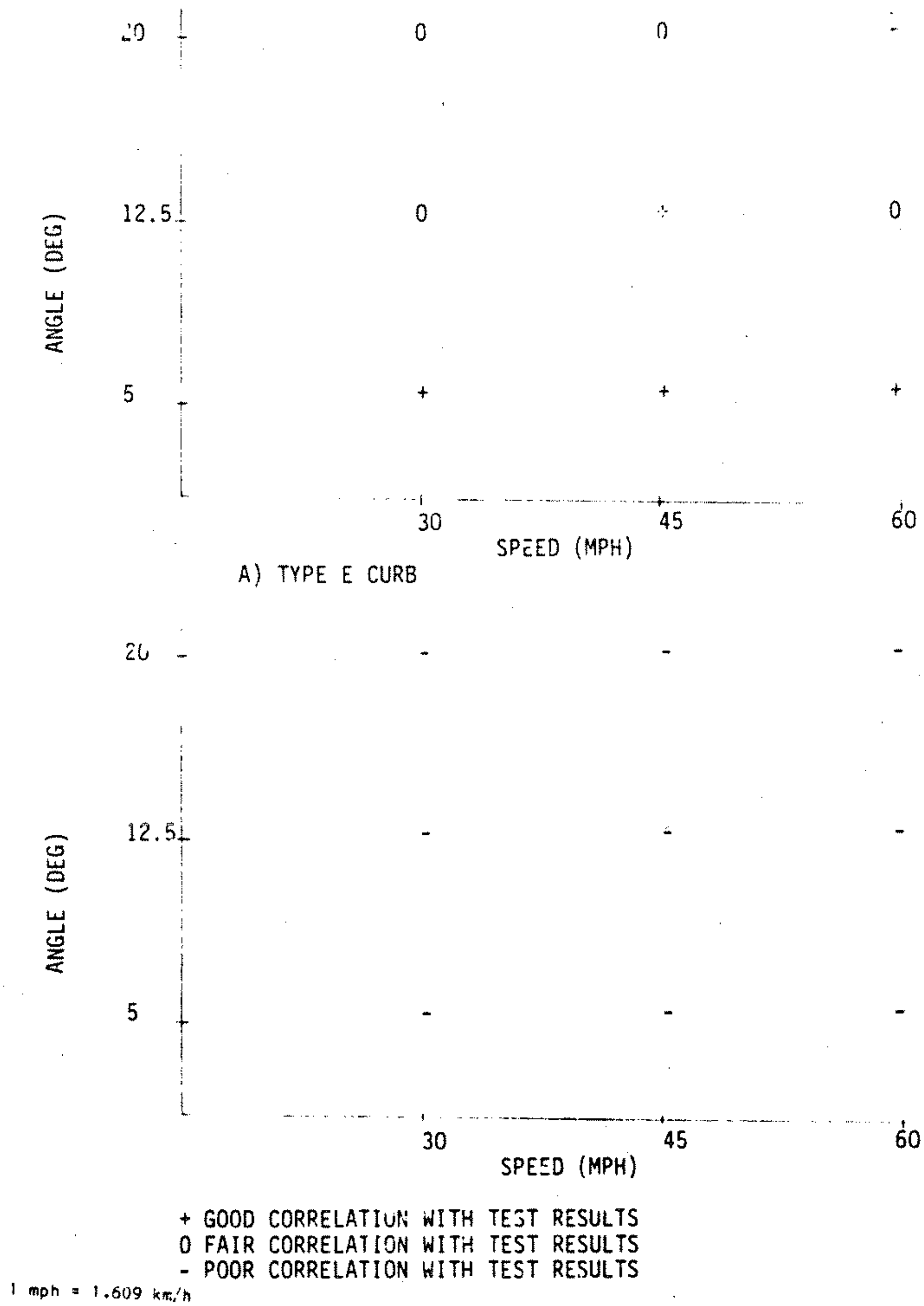


Figure 32 ROLL AND PITCH ANGLE RESPONSE EVALUATION

cases the comparisons were poor. This is due largely to the fact the the simulated vehicle redirected away from the curb while the test vehicle continued to cross the curb.

Angular response evaluations are shown in figure 32. In this case both vehicle roll angle and pitch angle are considered in the evaluations. As can be seen, simulated vehicle response for the type E curb are generally in either fair or good agreement with test vehicle response. However, for the type C curb, the simulated vehicle responses were judged poor in comparison to the test vehicle response in all cases. Again, this is generally due to the poor trajectory predicition for the type C curb.

These results generally indicate that a modeling limitation exist in the current treatment of tire/curb interactions that is sensitive to the type of curb being simulated. It is suspected that this limitation becomes evident with the type C curb due to a steeper slope than exists with the type E curbs. That is, the current tire/curb algorithm appears better suited to the less steep slope of the type E curb.

The nature of the modeling limitation that produces the results shown here is not able to be specifically identified as a result of this study; however, a number of areas are likely to be contributors. These include:

- The thin disk tire representation which lacks consideration of lateral enveloping power and direct production of lateral forces due to interference with the curb. These limitations would appear to be of increasing significance as the curb slope increases.

- The aligning torque representation which is simulated by the tire lateral force multipled by a constant pneumatic trial. Aligning torque produced by typical tires is known to be highly nonlinear with slip angle (and therefore lateral force) and actually reverses direction at high slip angles. This may result in a poor representation of the actual torque applied to the steering system under some conditions.

- The vertical tire stiffness representation as represented by a bilinear spring. This representation of tire vertical stiffness may be appropriate in situations with small vertical distribuances; however, significant tire vertical deflections can be encounterd during curb traversals. The actual behavior of tire stiffness at extreme deflections is, however, not kwown.

In addition to these modeling limitations which may play a significant factor in simulated vehicle responses to curb traversals, the sensitivity study of vehicle parameters has shown that some items of input data can have a substantial effect on vehicle responses. Suspension damping and the tire deflection at which bottoming occurs can have a substantial effect on vertical and angular responses of the vehicle, particuarly at higher encroachment angles. Steering system fricton can have a significant effect on predicted vehicle trajectory if large variations are considered. However, vehicle responses are less sensitive to nominal variations about a reasonable value of this parameter (as determined by measurement). Steering system inertia changes can also cause differences in vehicle trajectory responses. Such variations appear to be more significant at low speed where the duration of the interaction between the tire and curb is long enough to cause a response in the steering system.

Although variations in bump stop locations and rates were not made during the sensitivity study, it is believed, based on results of other parameter variations, that these parameters can cause variations in vehicle vertical responses due to short duration high level forces acting on the vehicle body.

Thus, from the results of this study, it is apparent that a number of vehicle input parameters are significant in vehicle responses to curb impacts and should be specified accurately if a specific vehicle is to be simulated as in a validation study. These include:

- Tire vertical rate over an extreme range of deflections.
- Bump stop locations and rates.
- Suspension damping.

Other parameters that can influence vehicle response, but to a less significant extent as long as reasonable values are used include:

- Vehicle sprung mass inertias.
- Steering system friction.
- Steering system inertia.

In summary, based on the results of this study, the use of the HVOSM to simulate curb traversal should be undertaken only with the understanding that prediction may not always be valid. Modeling limitations appear to be more significant in effecting vehicle responses with some curbs than with others. The HVOSM predictions compared much more favorably with type E curb test results than with type C test results due, it is believed, to the nature of the modeling representation. Simulation predictions of vehicle responses to a type X curb were also not in agreement with test results. In addition, erroneous or improper specification of certain vehicle input parameters can effect the response prediction to a significant extent.

APPENDIX A

MGA DUPLICATION OF NCHRP 150 RUNS

Figures 33 through 50 show the HVOSM results of the MGA duplication of NCHRP 150 runs N-2 through N-19 plotted against the corresponding NCHRP 150 results. Each figure is a comparison of the full-scale NCHRP 150 results (denoted by the individual triangles and labeled "TEST"), the NCHRP 150 simulation results (denoted by the dashed line and labeled "NCHRP 150"), and the results of MGA's duplication of the NCHRP 150 simulation runs (denoted by the line with the box symbols and labeled "MGA REPEAT OF NCHRP 150"). Each figure is composed of two parts. Part (a) plots vehicle pitch angle, roll angle, and bumper height 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.

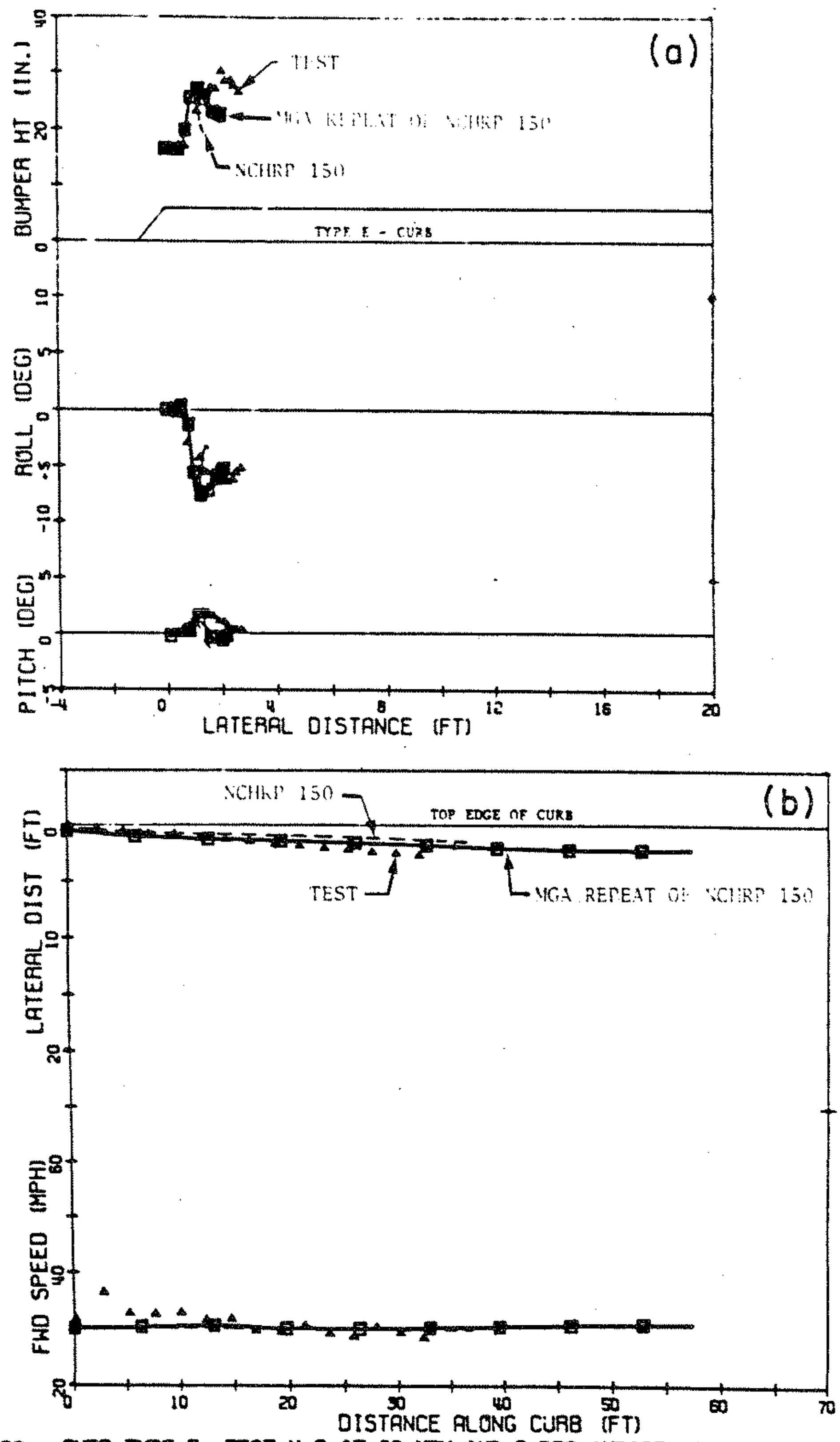


Figure 33 CURB TYPE E, TEST N-2 AT 30-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

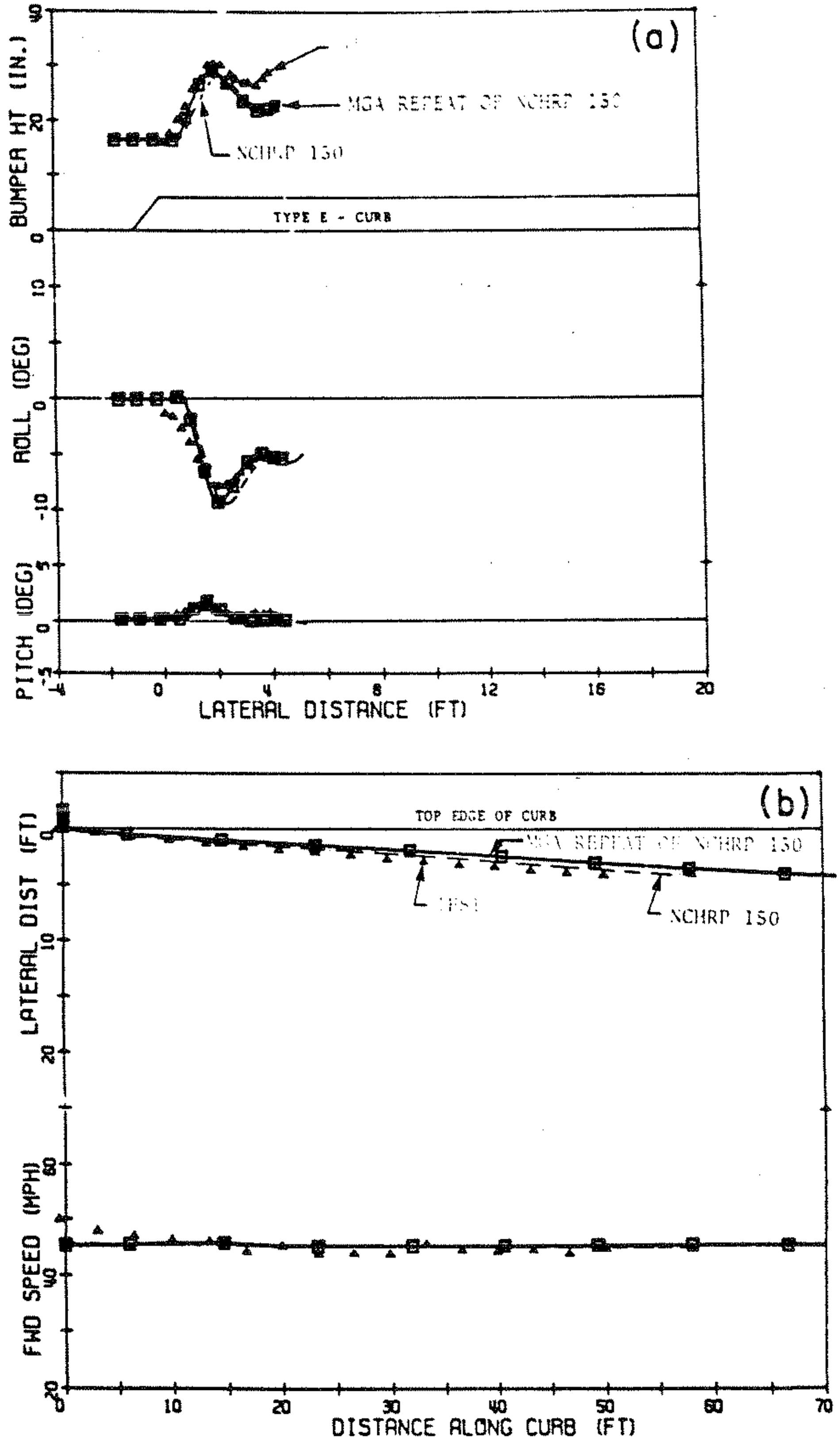


Figure 34 CURB TYPE E, TEST N-3 AT 45-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

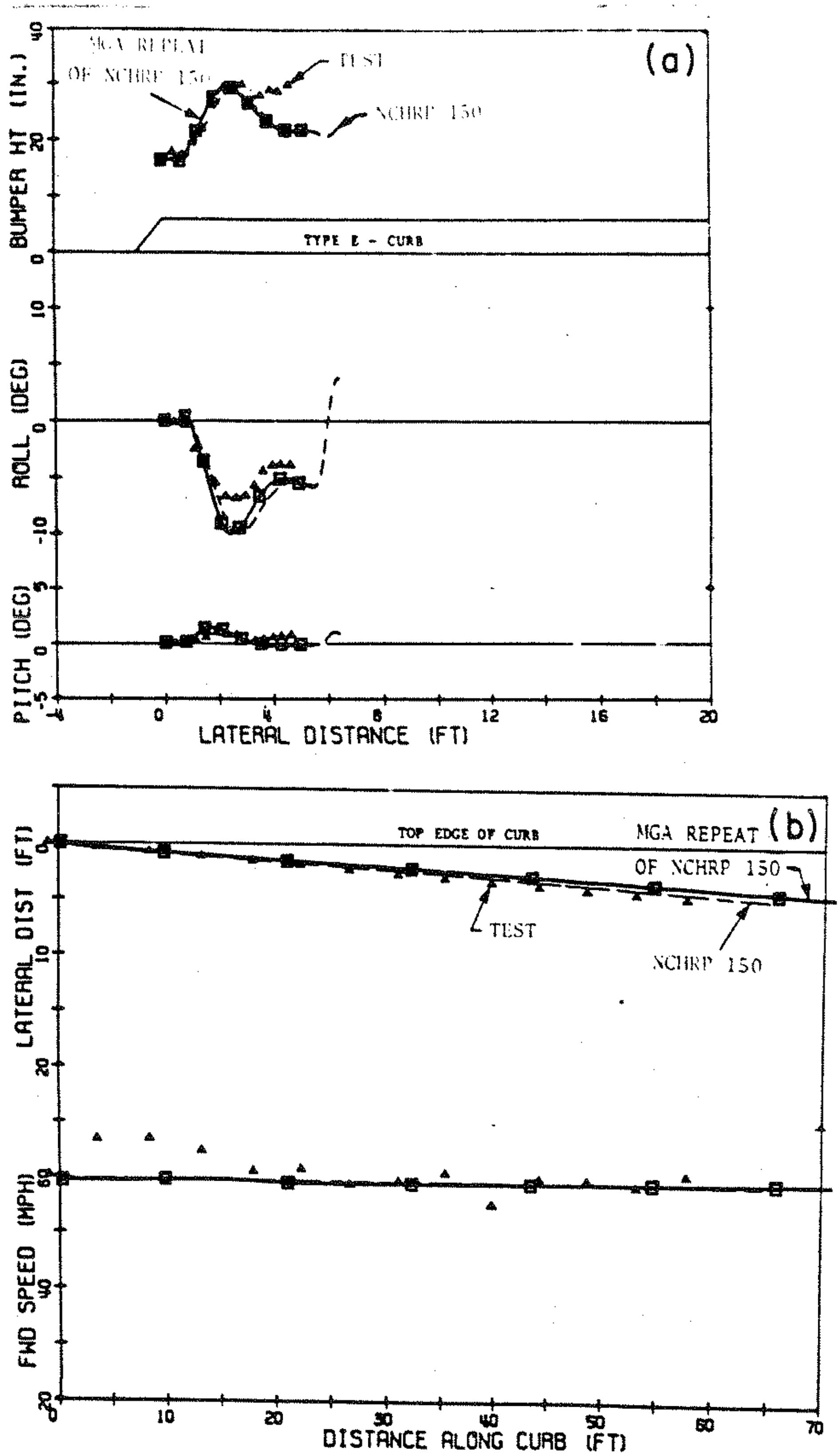


Figure 35 CURB TYPE E, TEST N-4 AT 60-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

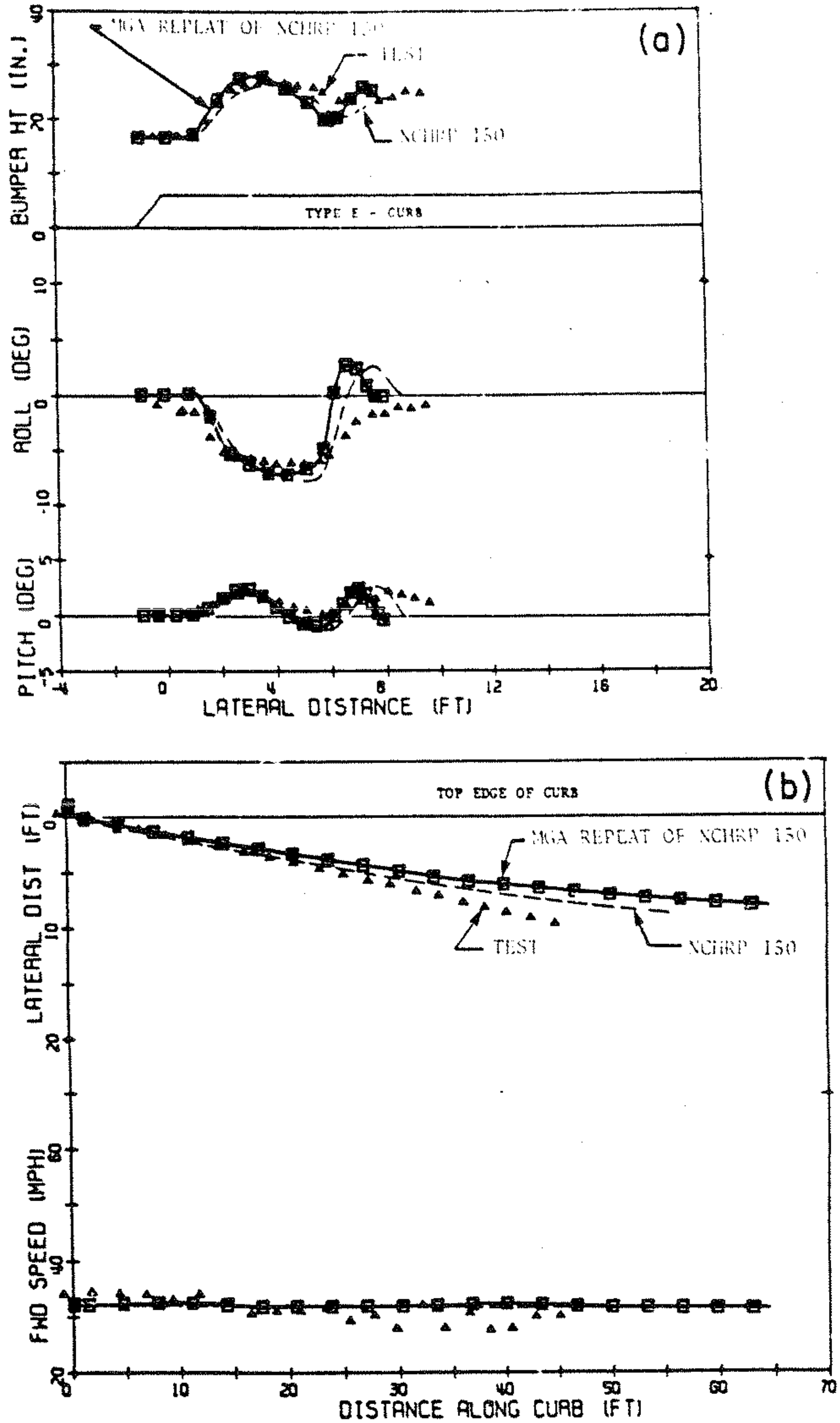
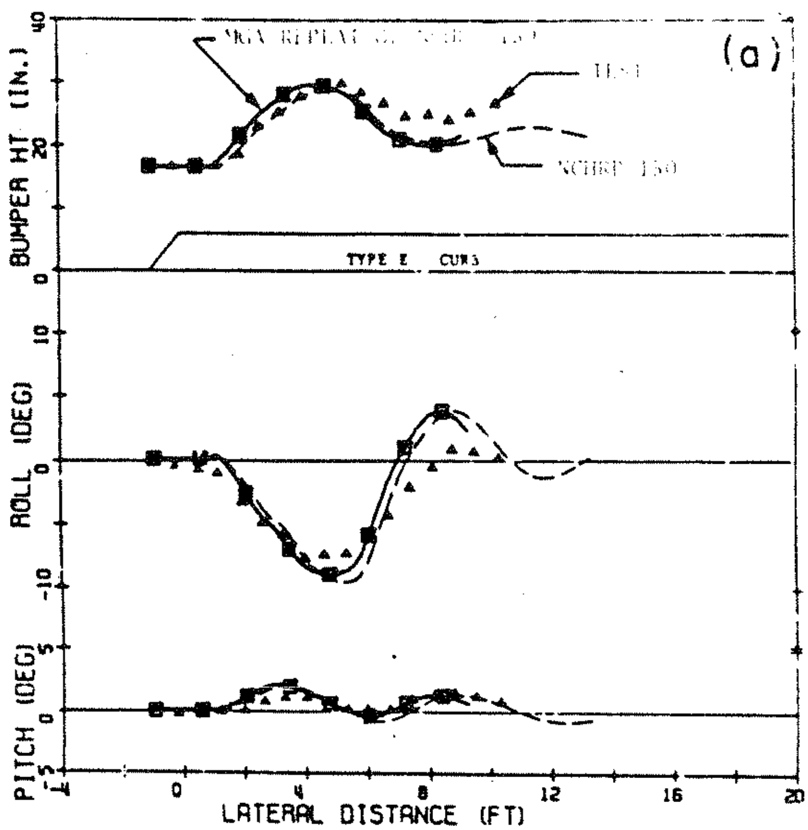


Figure 36 CURB TYPE E, TEST N-5 AT 30-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h



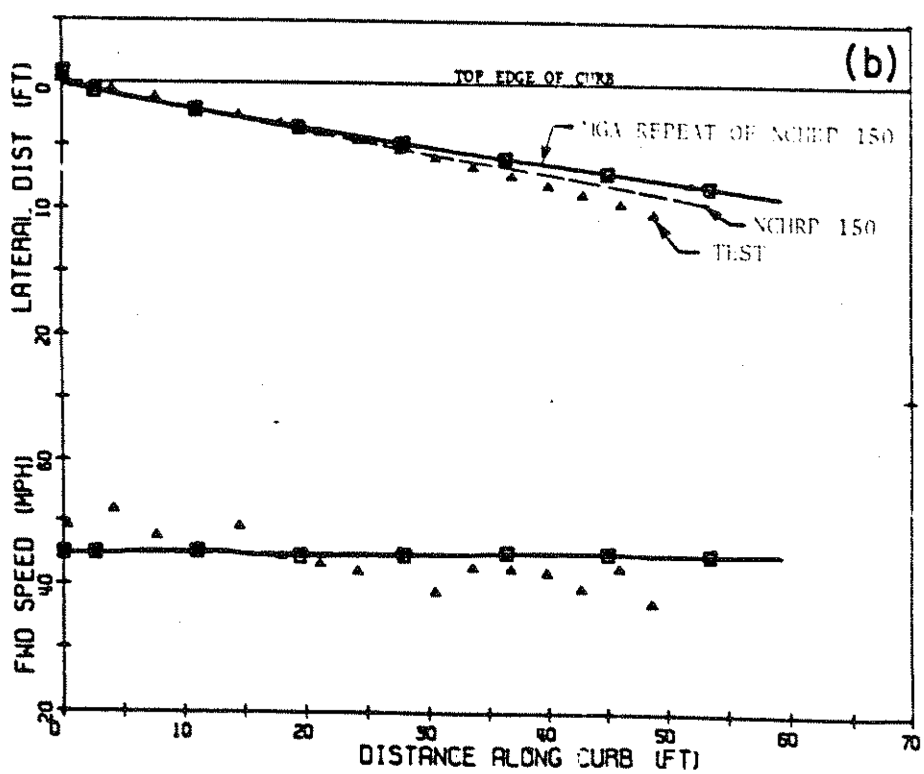


Figure 37 CURB TYPE E, TEST N-6 AT 45-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

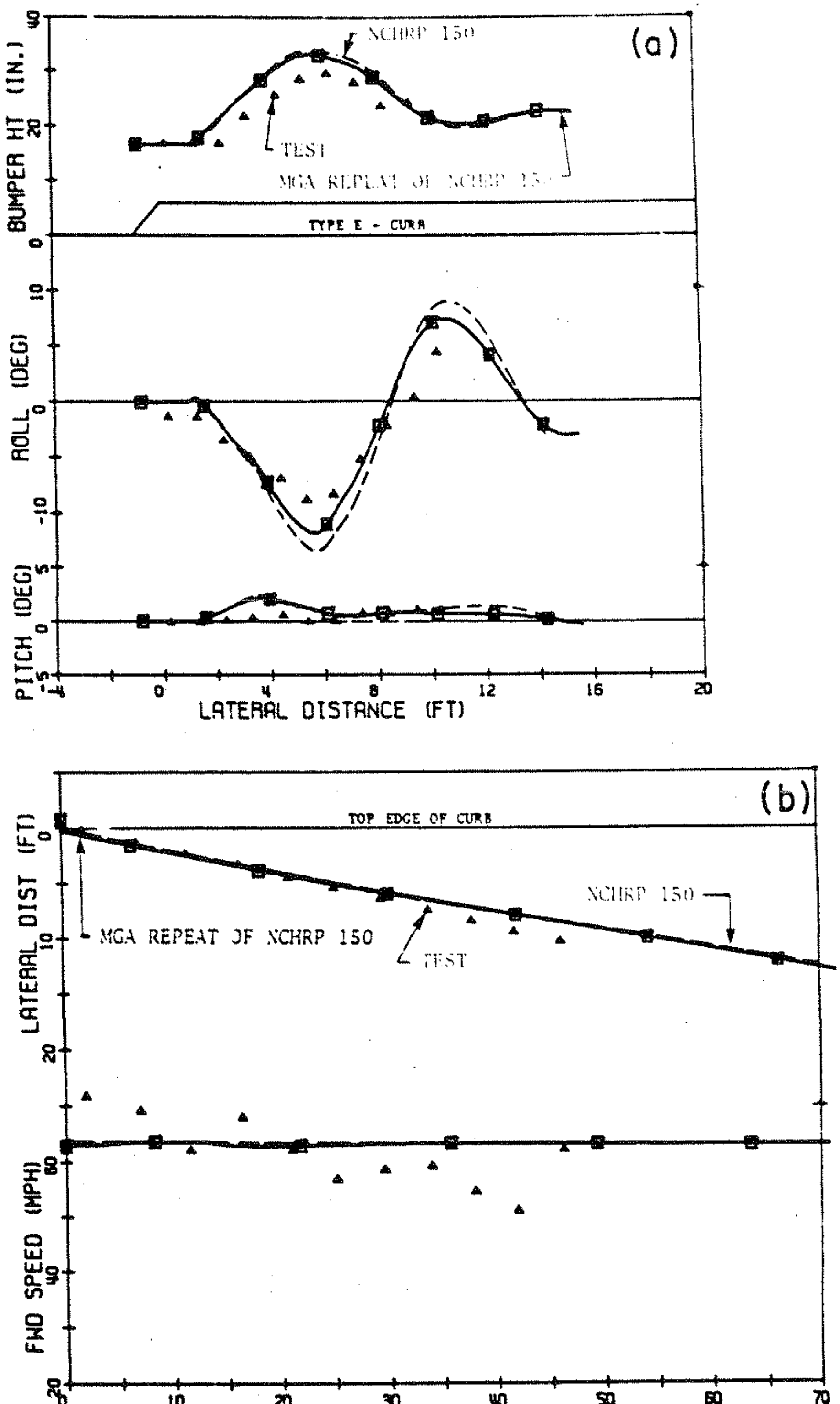


Figure 38 CURB TYPE E, TEST N-7 AT 60-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

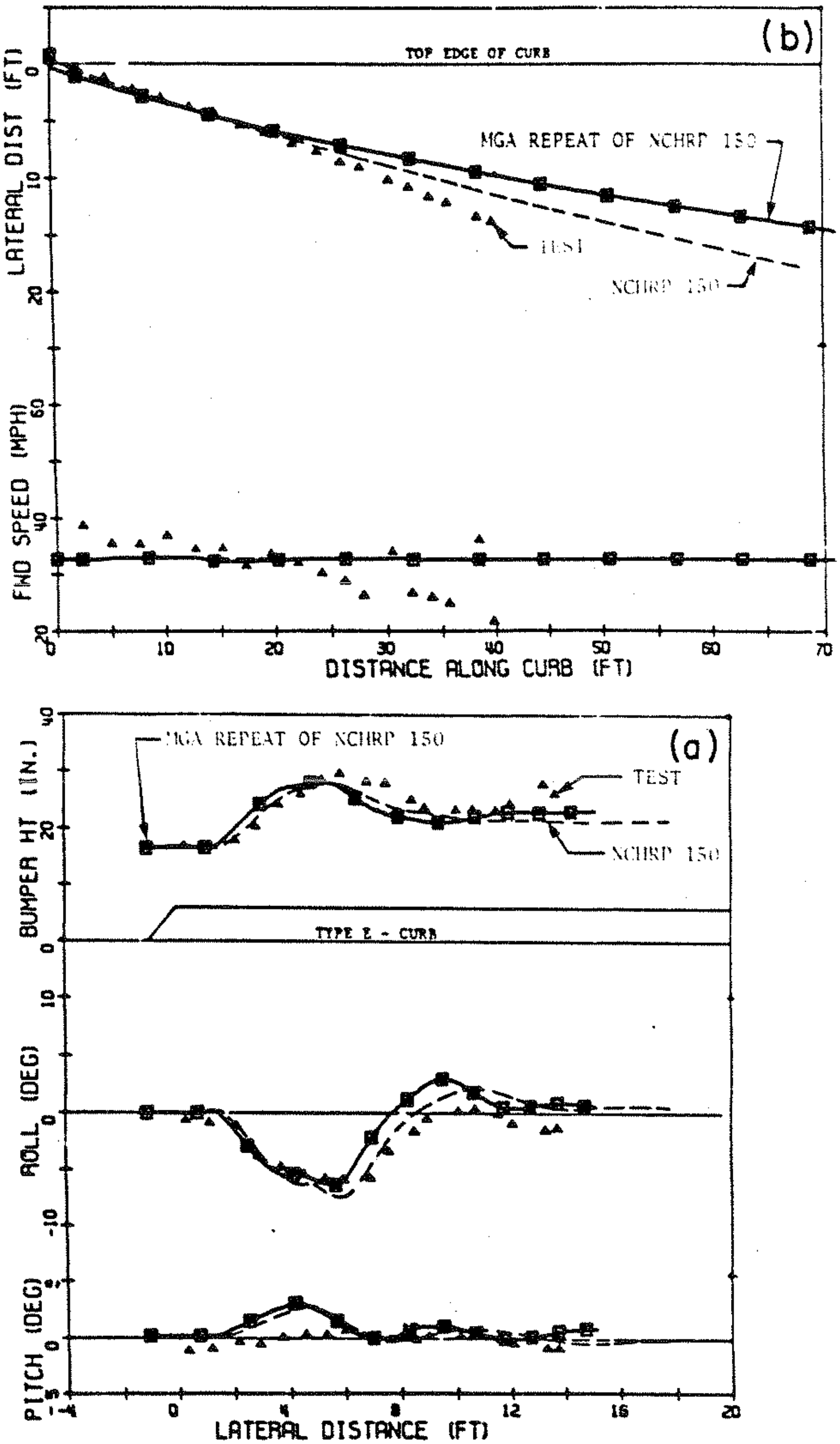


Figure 39 CURB TYPE E, TEST N-8 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

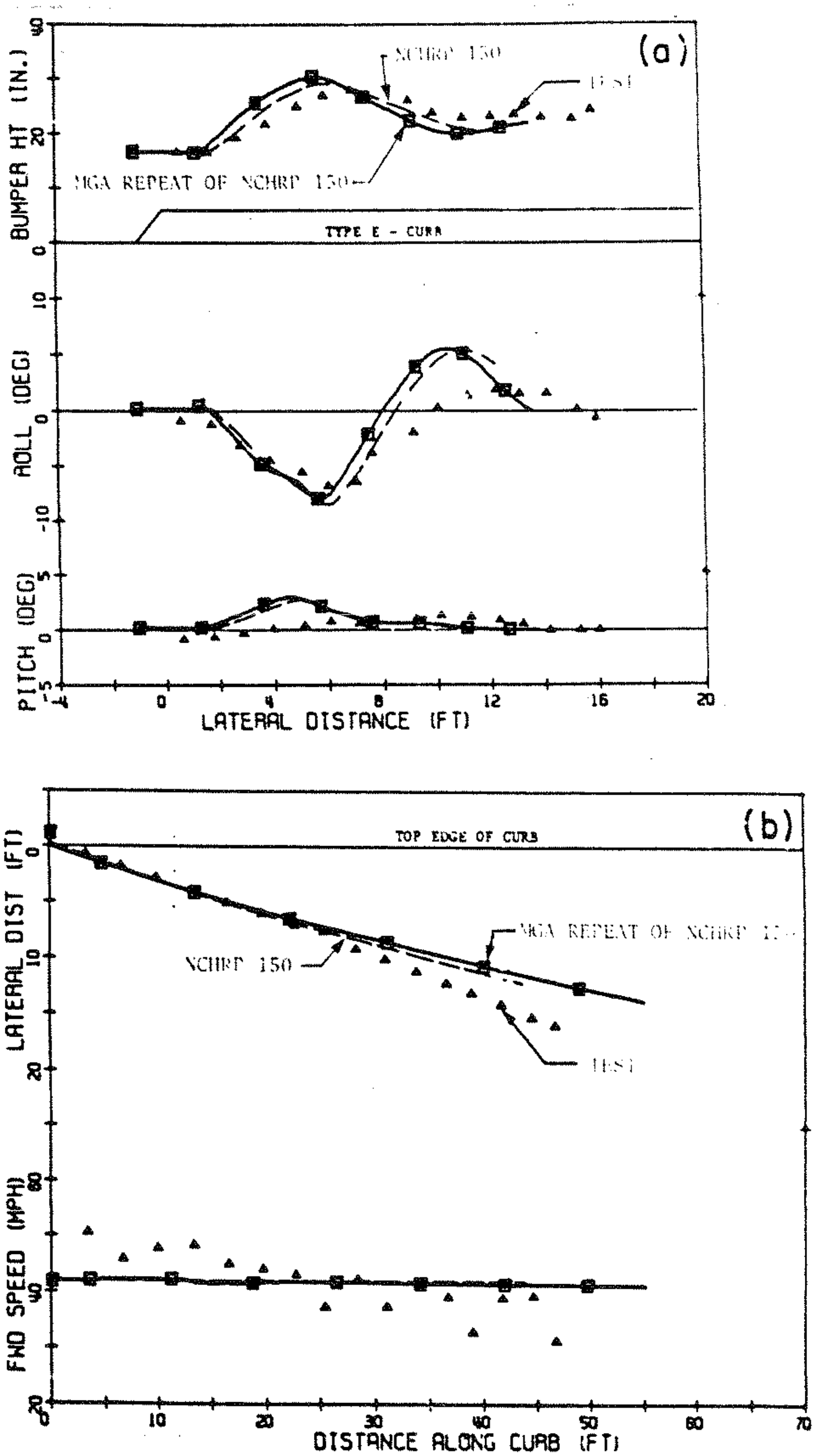


Figure 40 CURB TYPE E, TEST N-9 AT 45-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

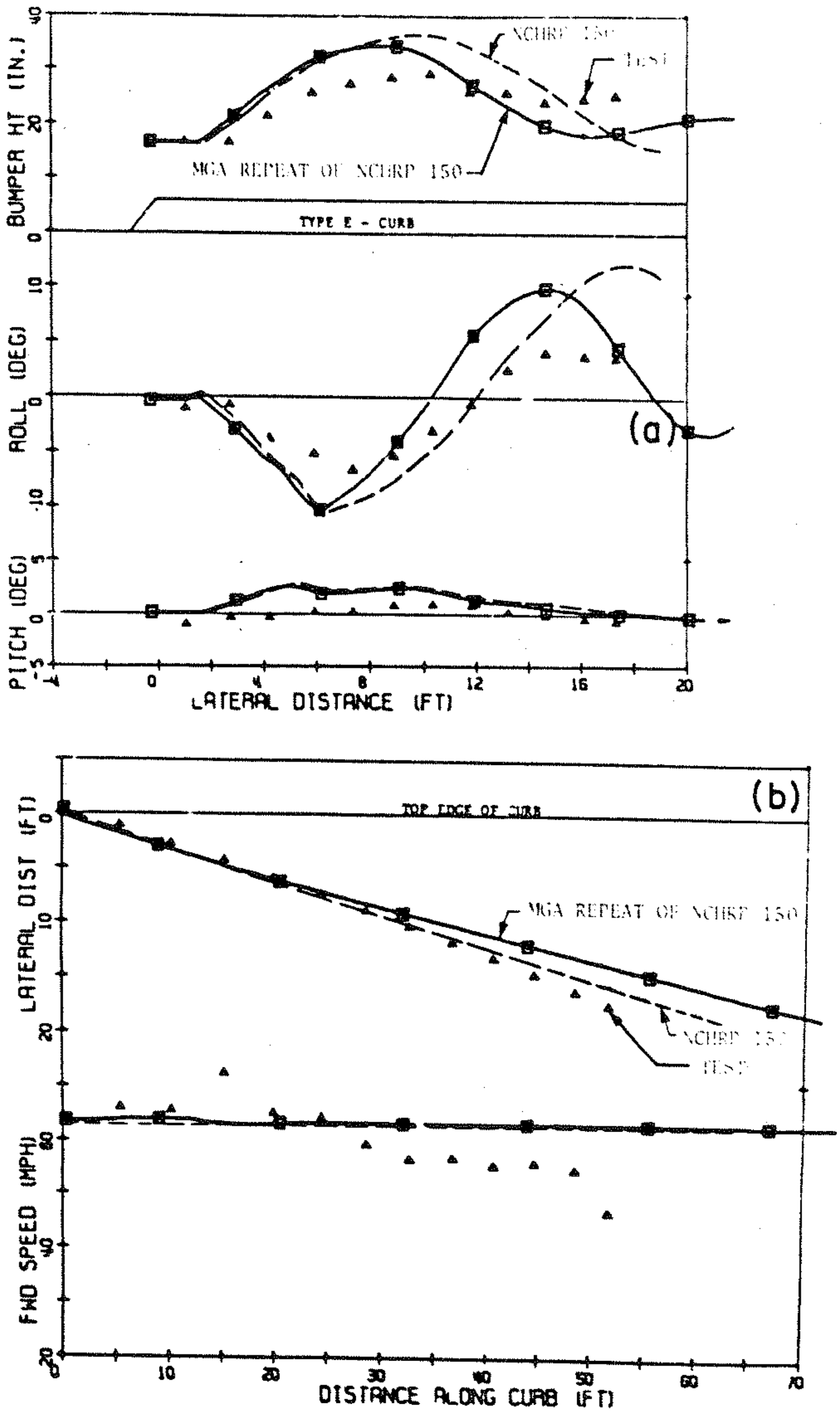


Figure 41 CURB TYPE E, TEST N-10 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

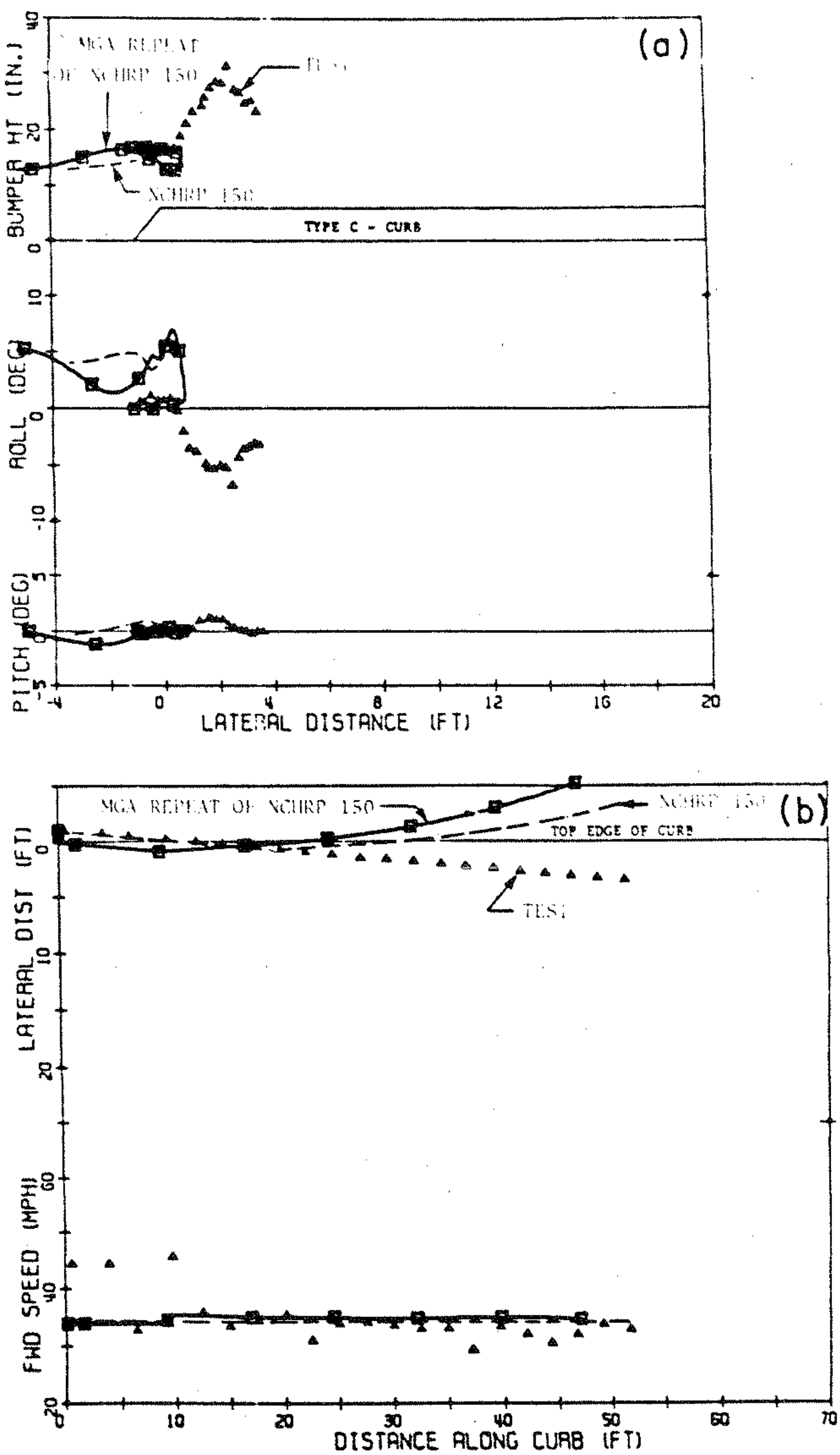


Figure 42 CURB TYPE C, TEST N-11 AT 30-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

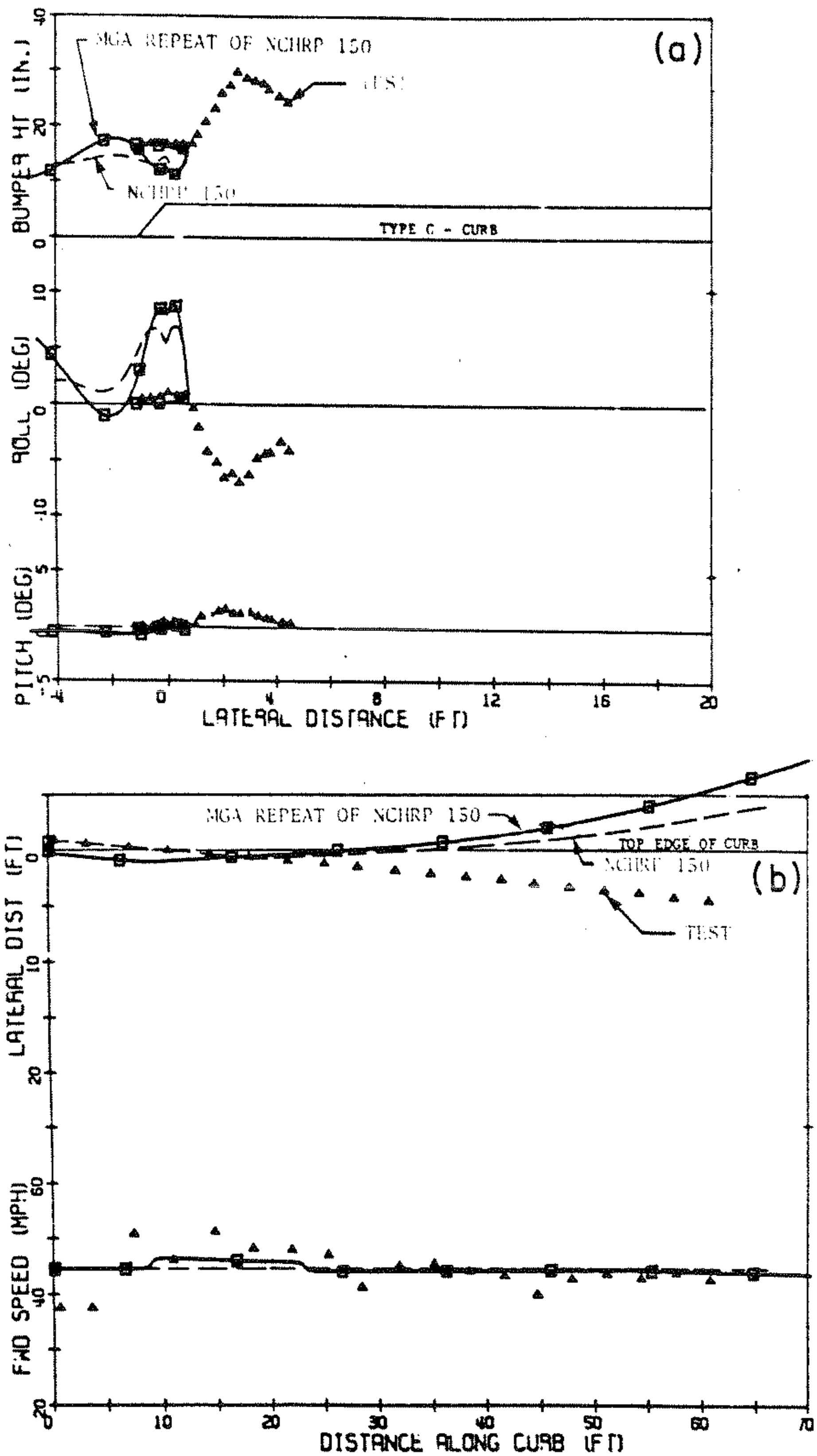
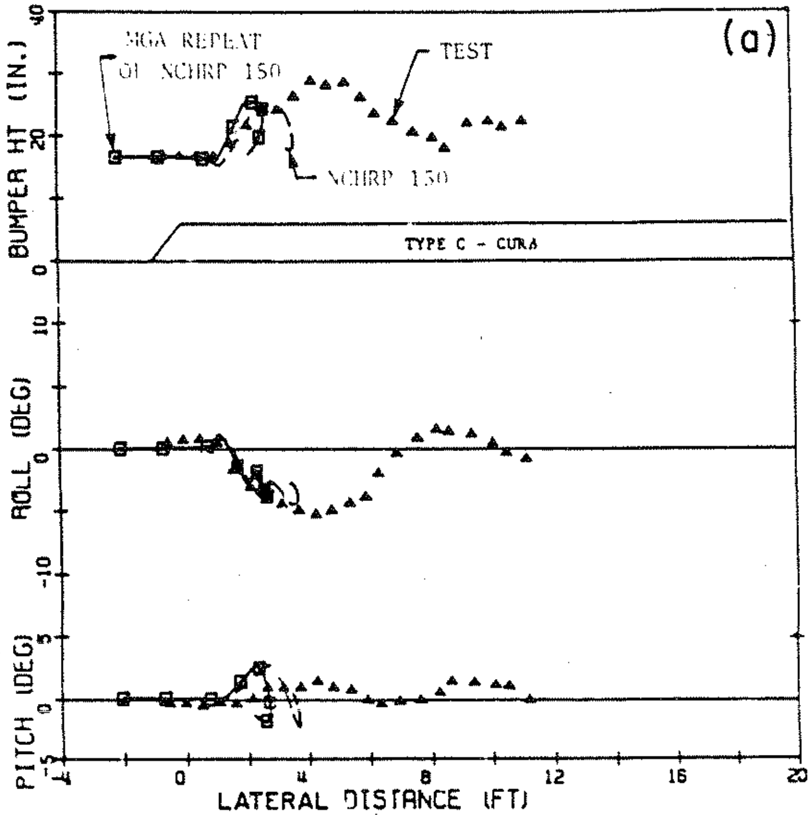


Figure 43 CURB TYPE C, TEST N-12 AT 45-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h



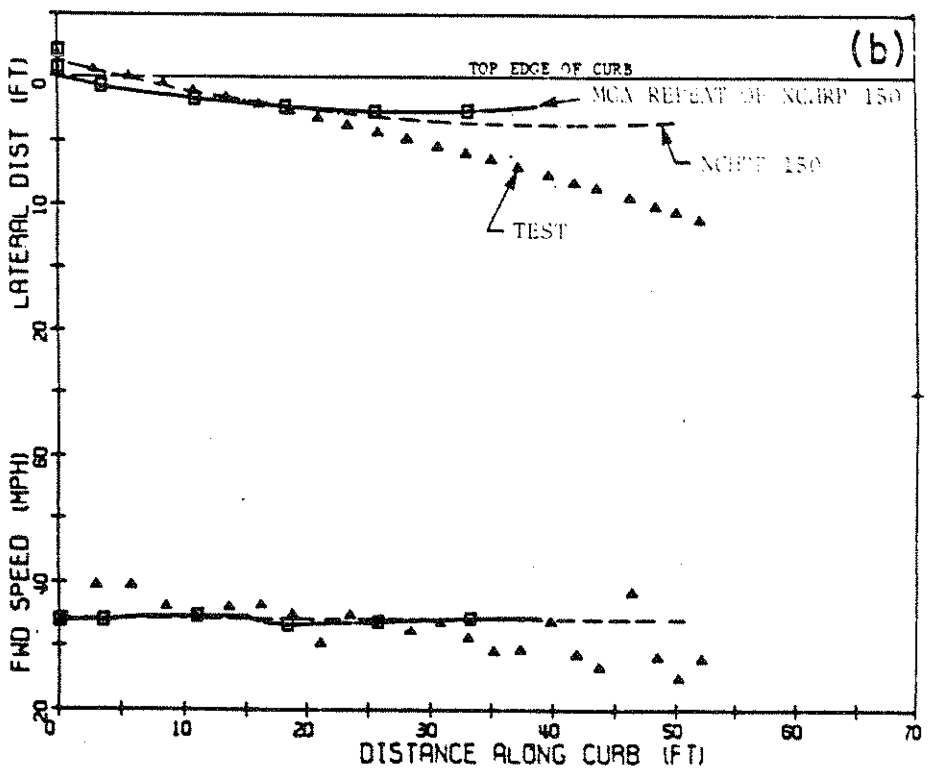


Figure 44 CURB TYPE C, TEST N-13 AT 30-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

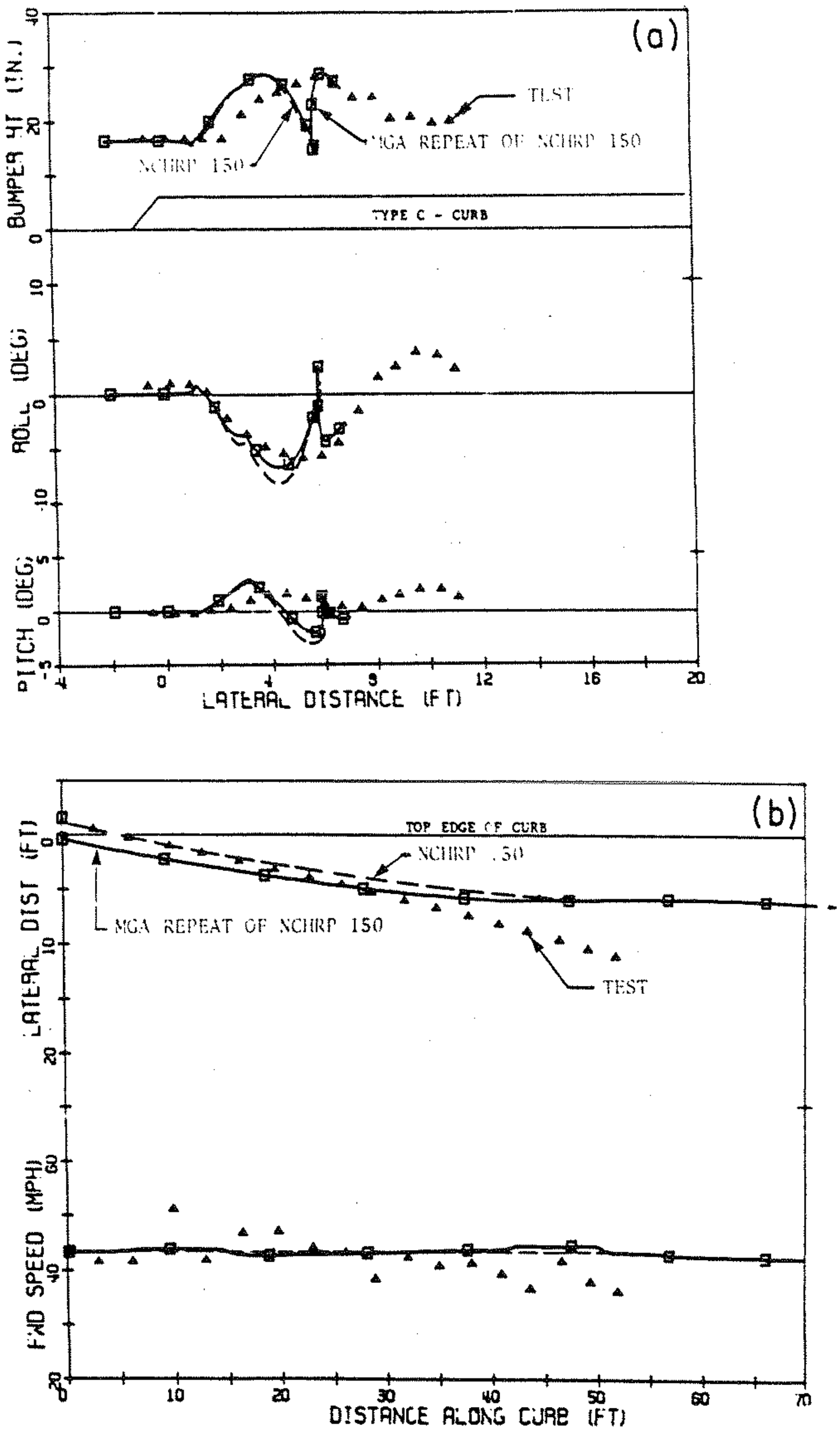


Figure 45 CURB TYPE C, TEST N-14 AT 45-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

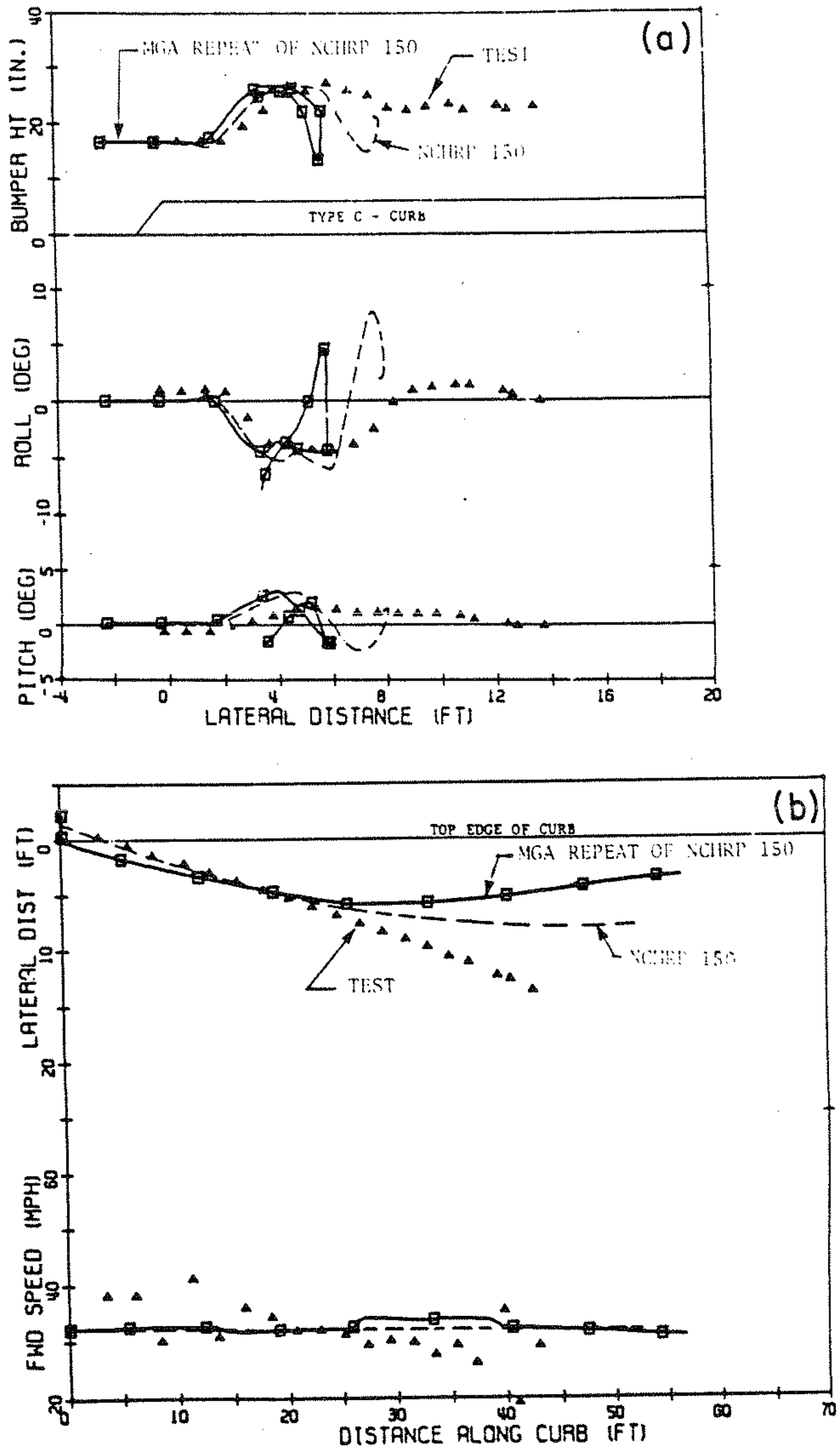


Figure 46 CURB TYPE C, TEST N-15 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

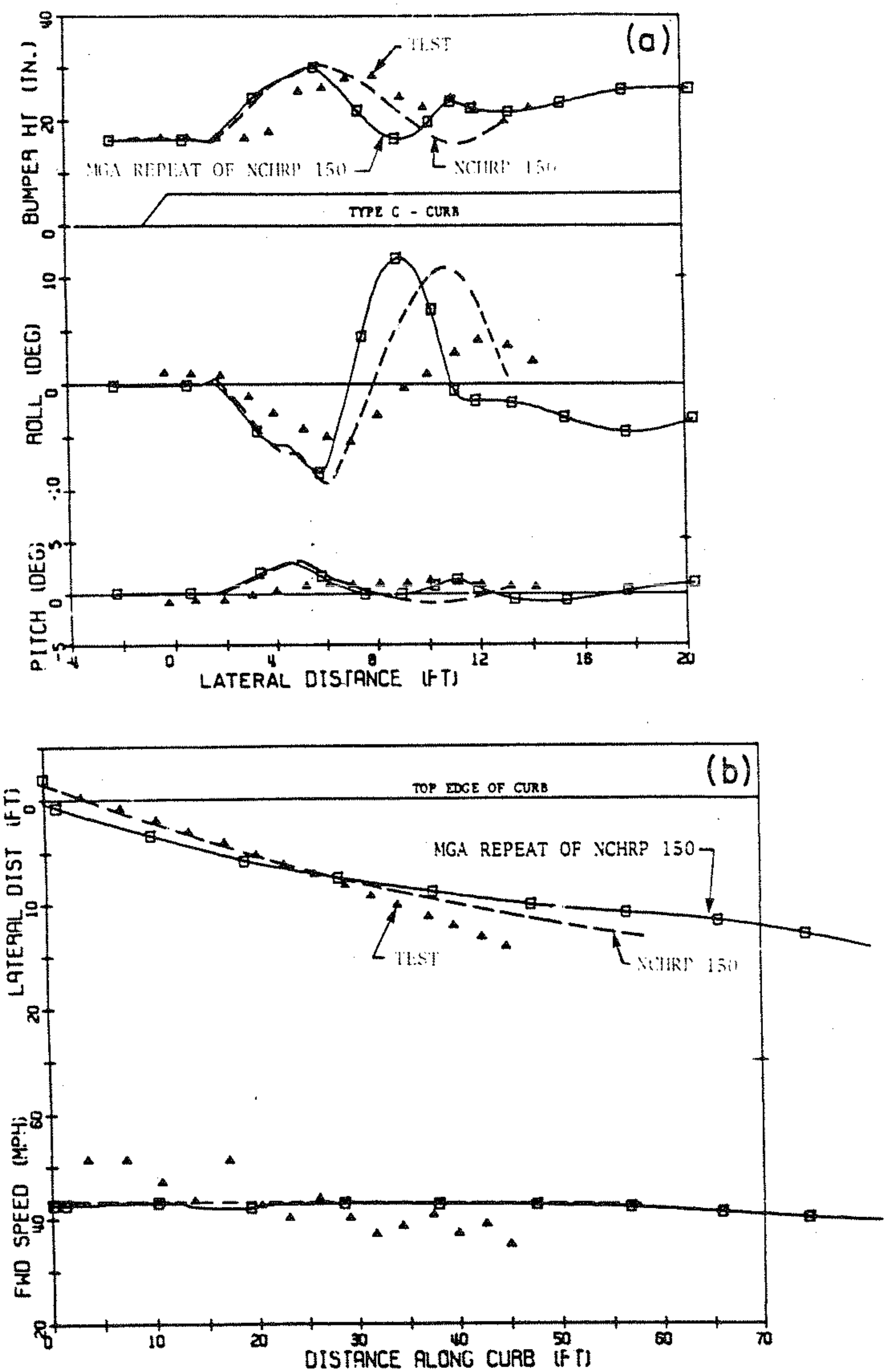


Figure 47 CURB TYPE C, TEST N-16 AT 45-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

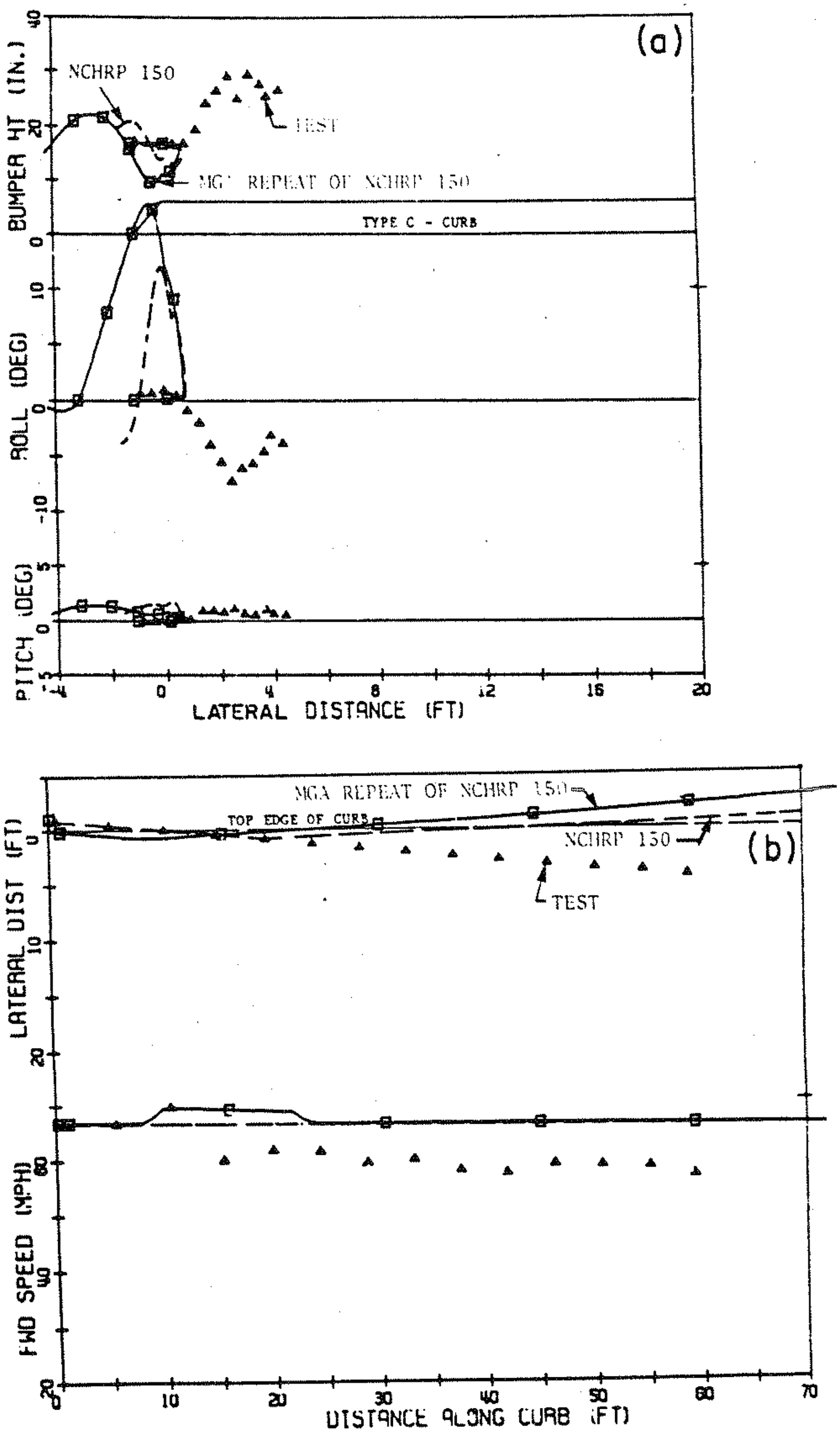


Figure 48 CURB TYPE C, TEST N-17 AT 60-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

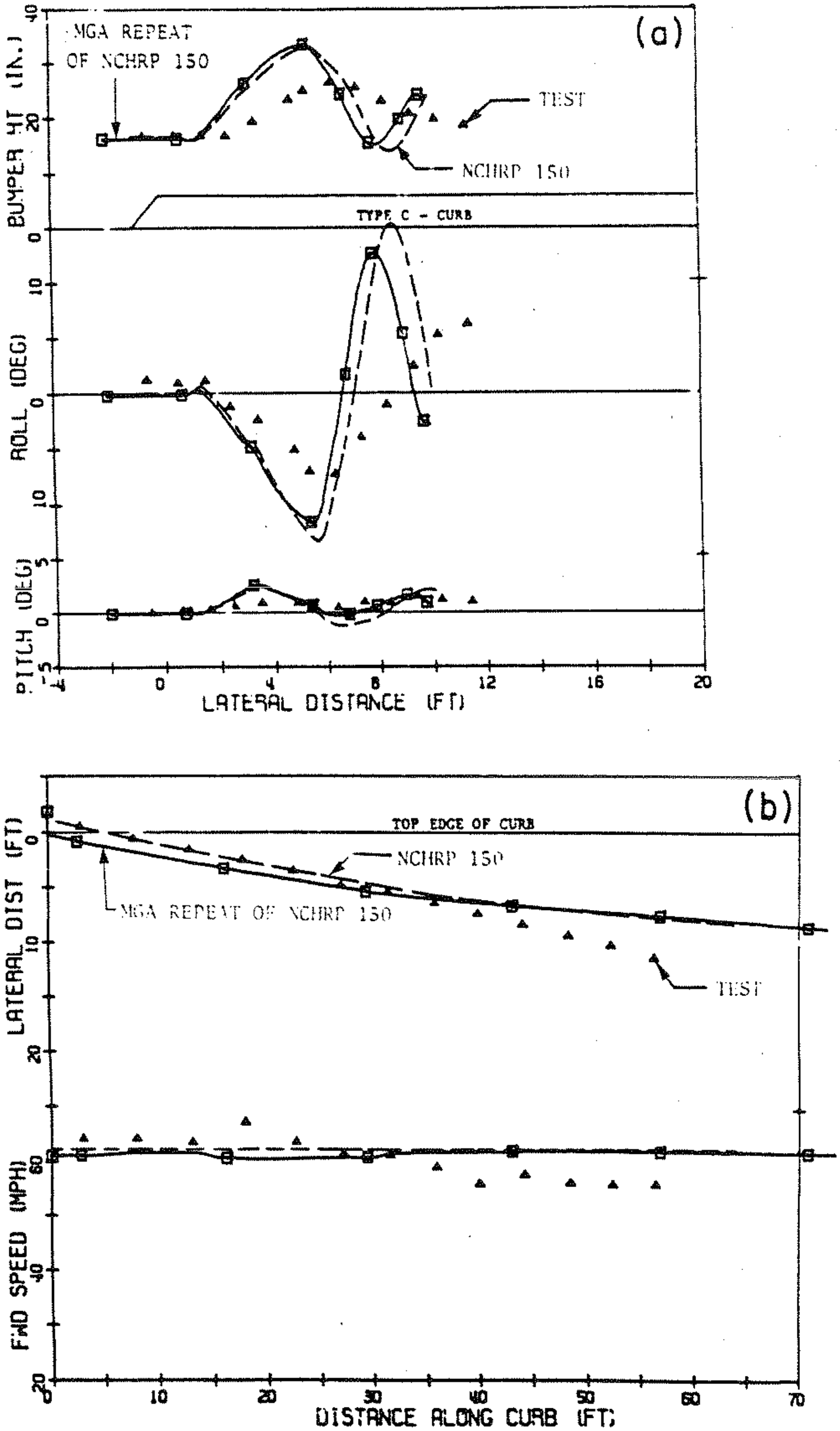


Figure 49 CURB TYPE C, TEST N-18 AT 60-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

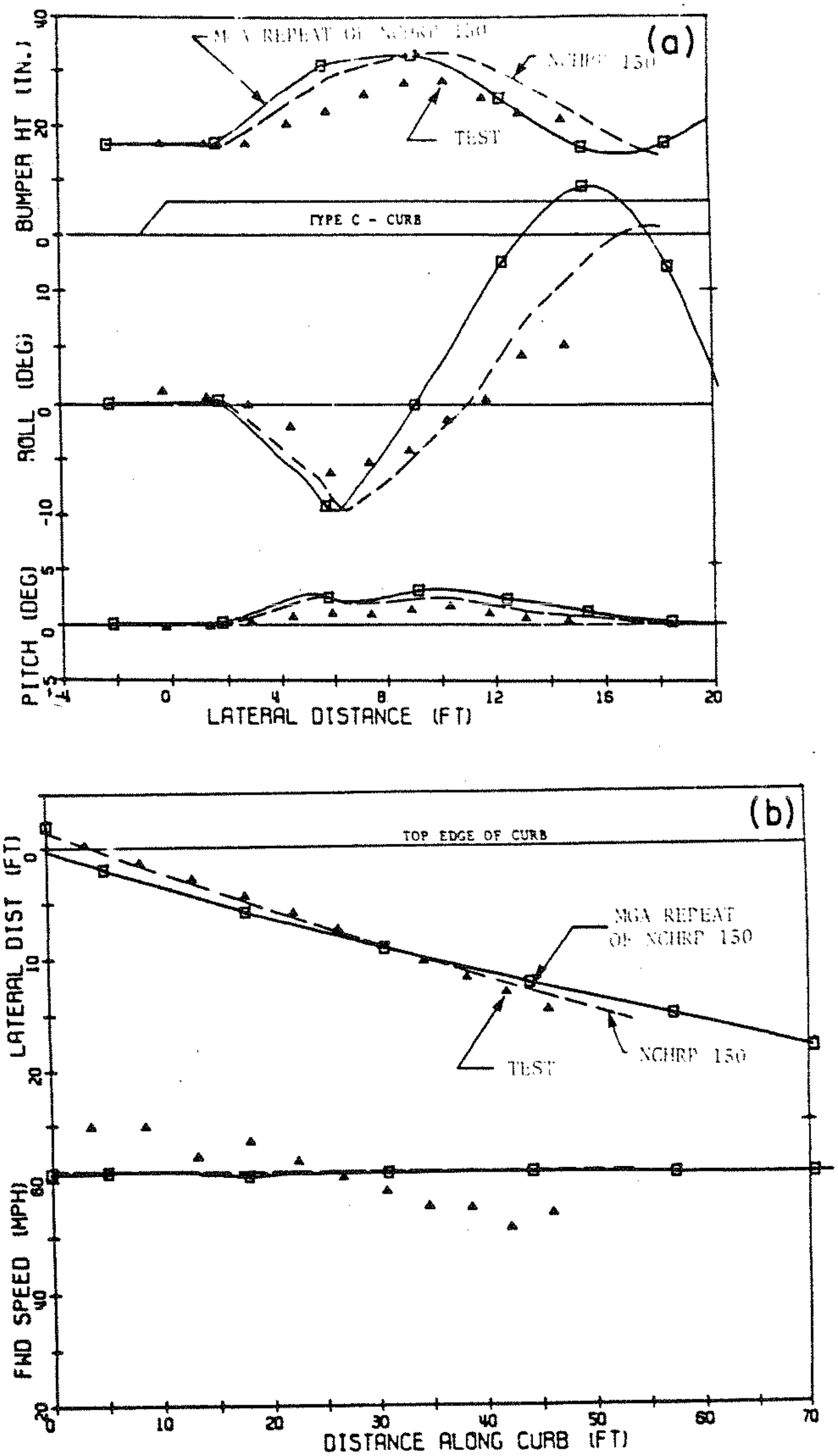


Figure 50 CURB TYPE C, TEST N-19 AT 60-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

APPENDIX B
MGA DUPLICATION OF MCI RUNS

Figures 51 through 68 show the HVOSM results of the MGA duplication of MCI's simulation of runs N-2 through N-19 plotted against the corresponding NCHRP 150 results. Each figure is a comparison of the full-scale NCHRP 150 results (denoted by the individual triangles and labeled "TEST"), the NCHRP 150 simulation results (denoted by the solid line and labeled "NCHRP 150"), and the results of MGA's duplication of MCI's simulation runs (denoted by the line with the box symbols and labeled "MGA REPEAT OF MCI"). Each figure is composed of two parts. Part (a) plots vehicle pitch angle, roll angle, and bumper height 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.

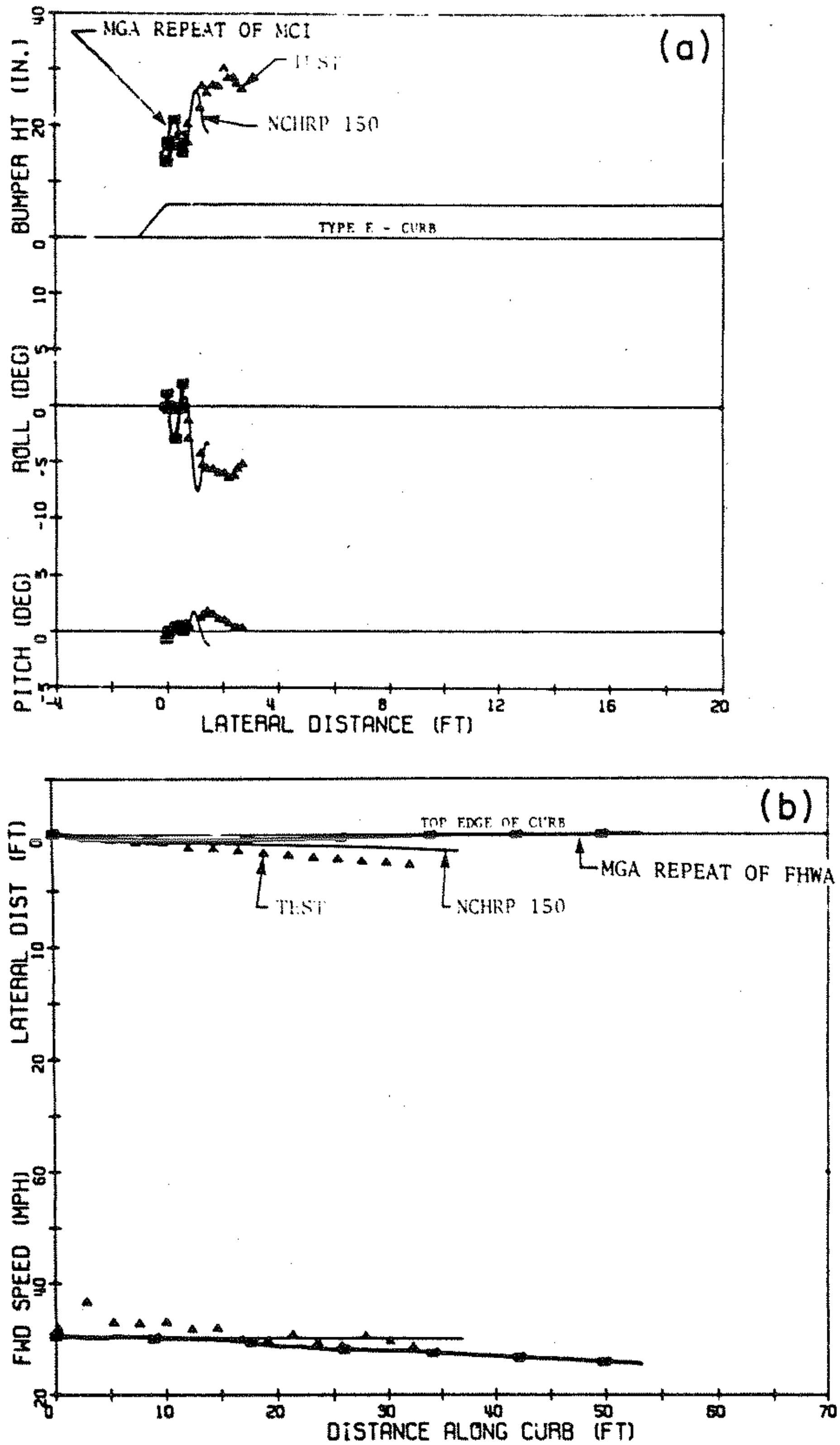


Figure 51 CURB TYPE E, TEST N-2 AT 30-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

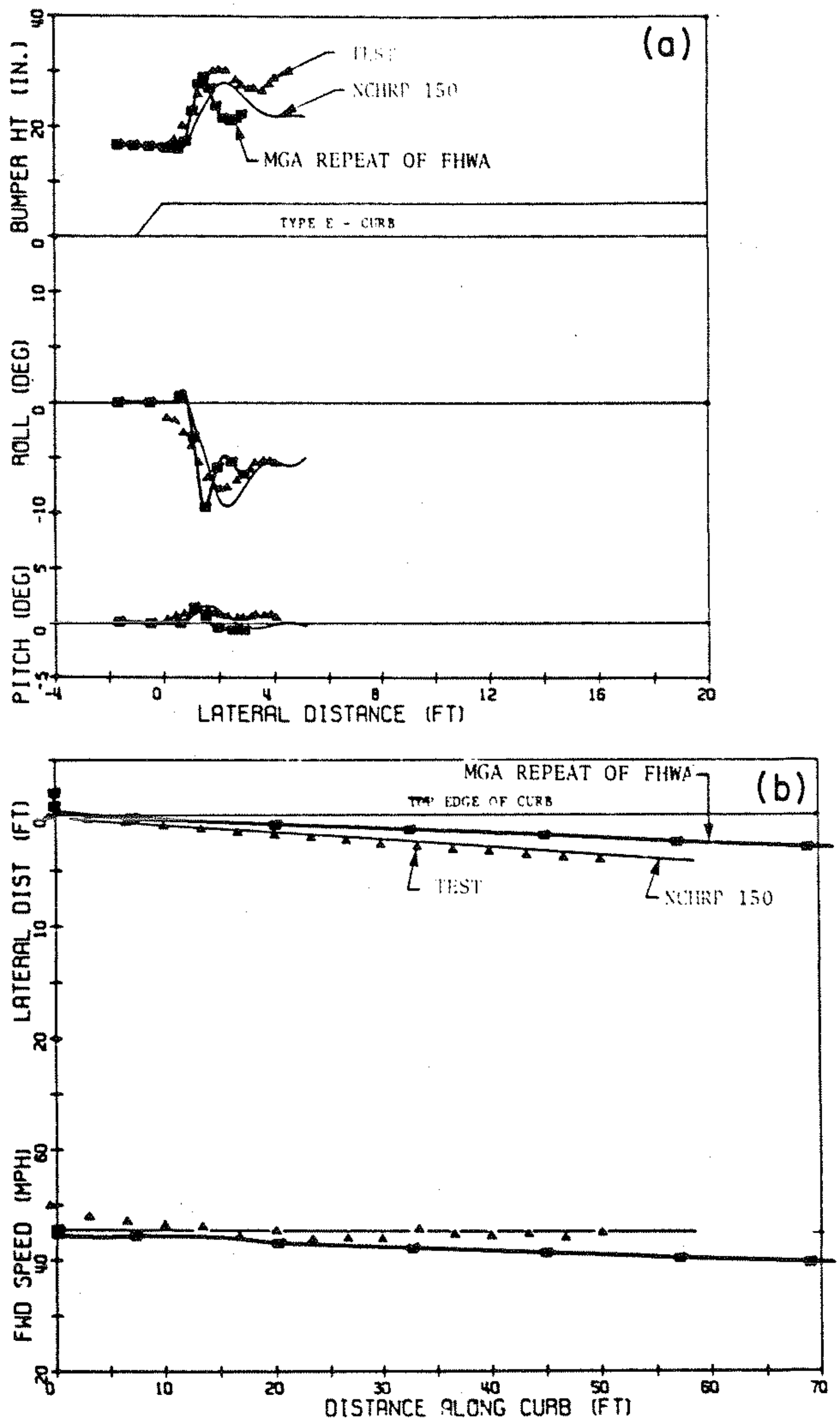


Figure 52 CURB TYPE E, TEST N-3 AT 45-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

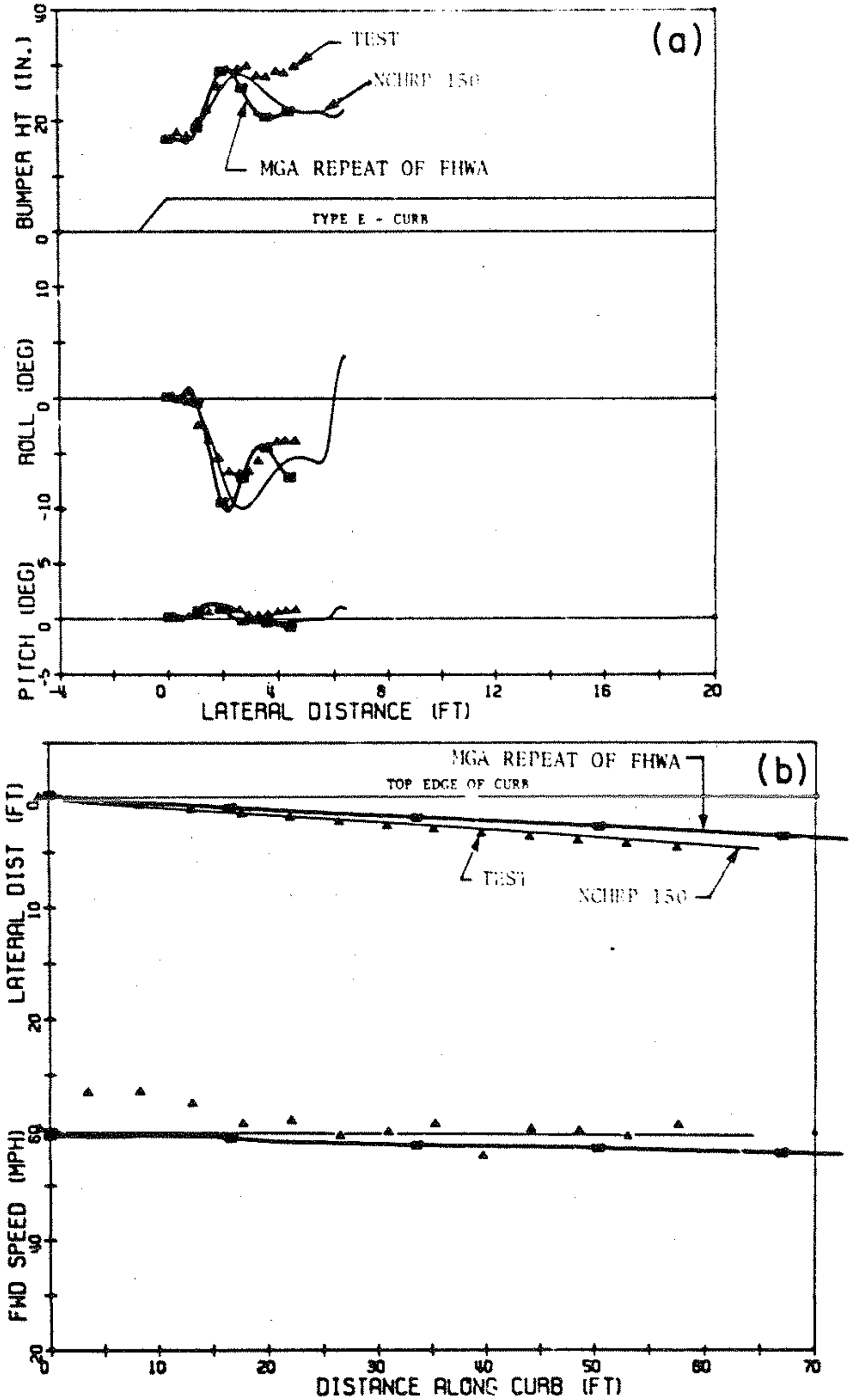


Figure 53 CURB TYPE E, TEST N-4 AT 60-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

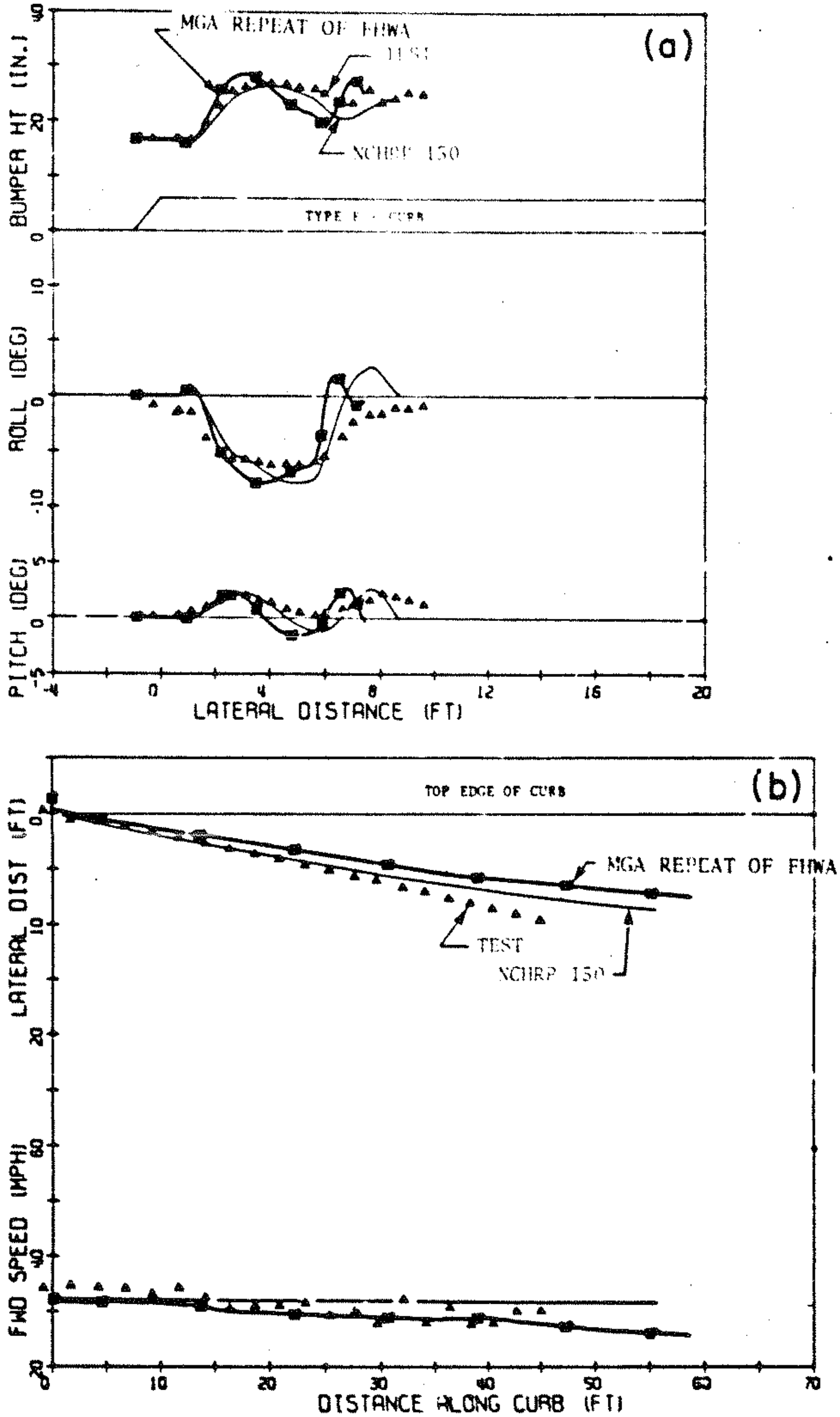


Figure 54 CURB TYPE E, TEST N-5 AT 30-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

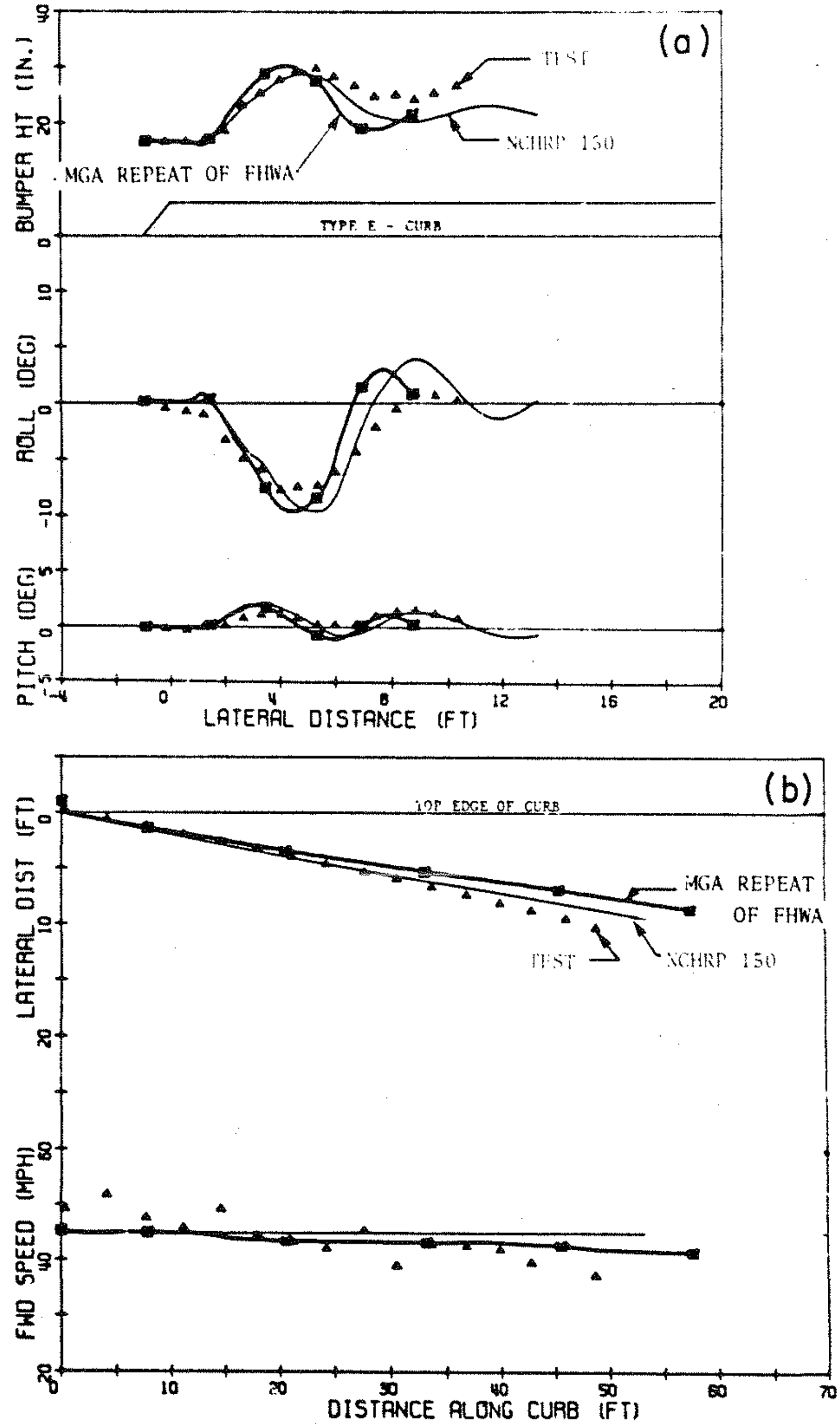


Figure 55 CURB TYPE E, TEST N-6 AT 45-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

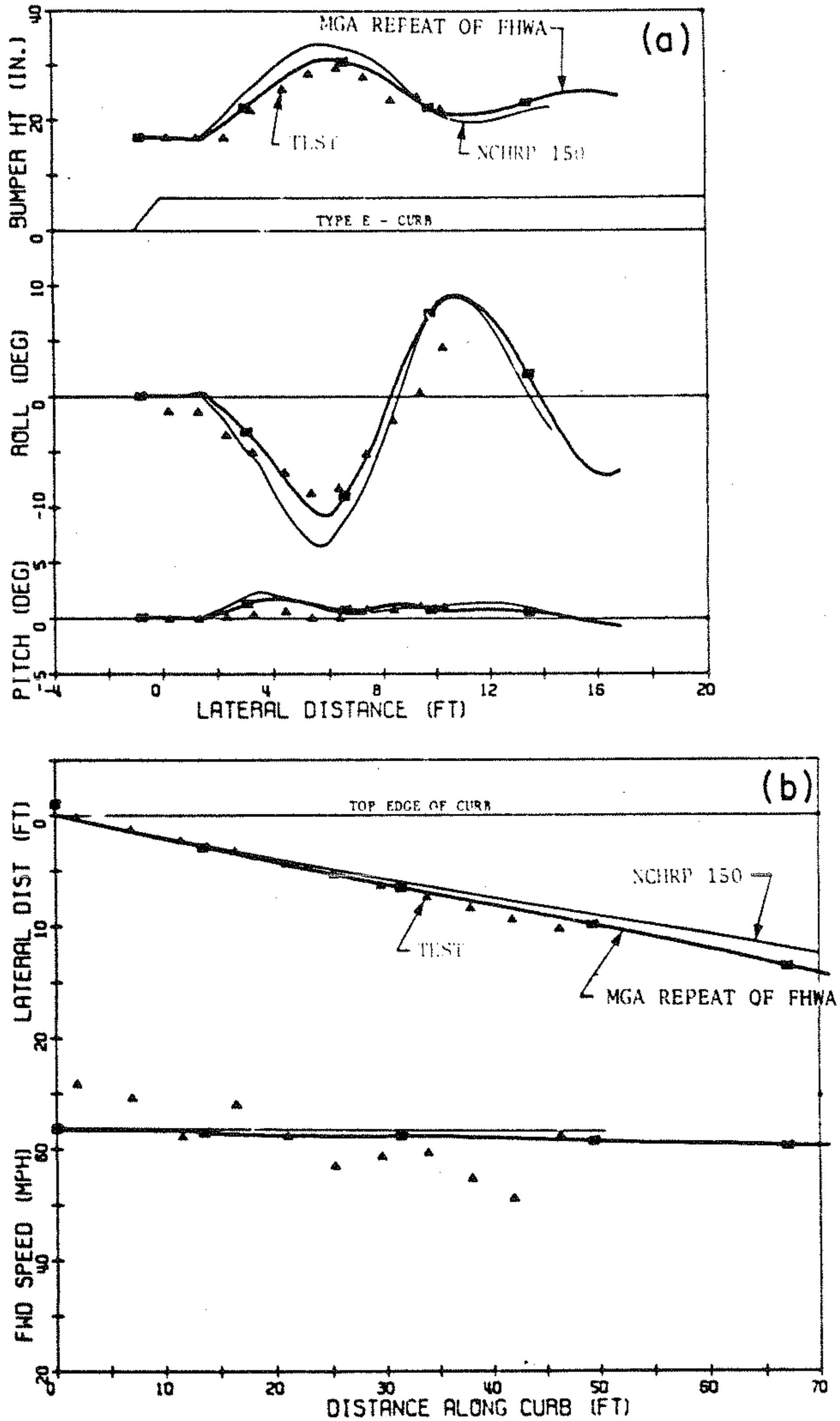


Figure 56 CURB TYPE E, TEST N-7 AT 60-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

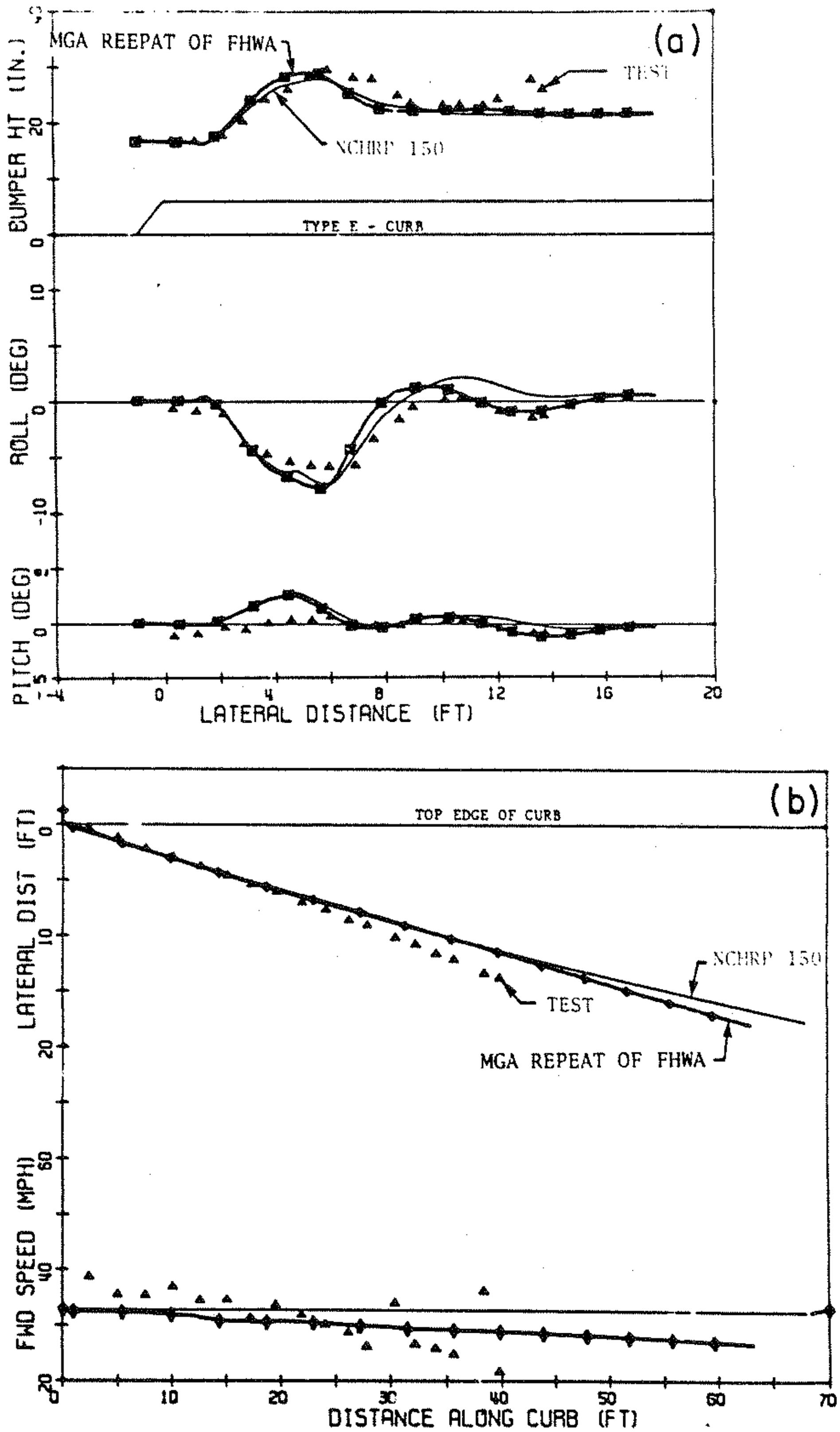


Figure 57 CURB TYPE E, TEST N-8 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

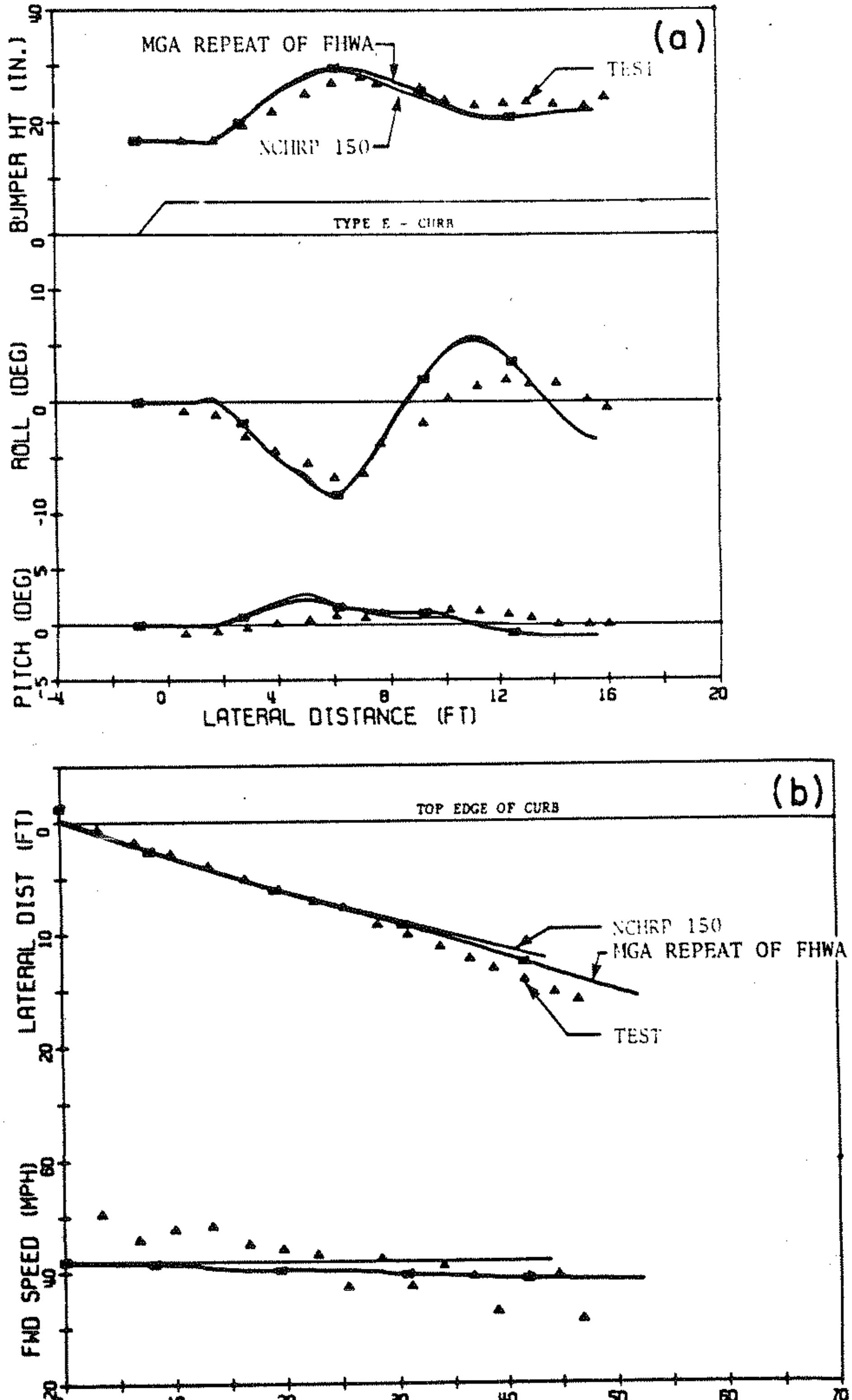


Figure 58 CURB TYPE E, TEST N-9 AT 45-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

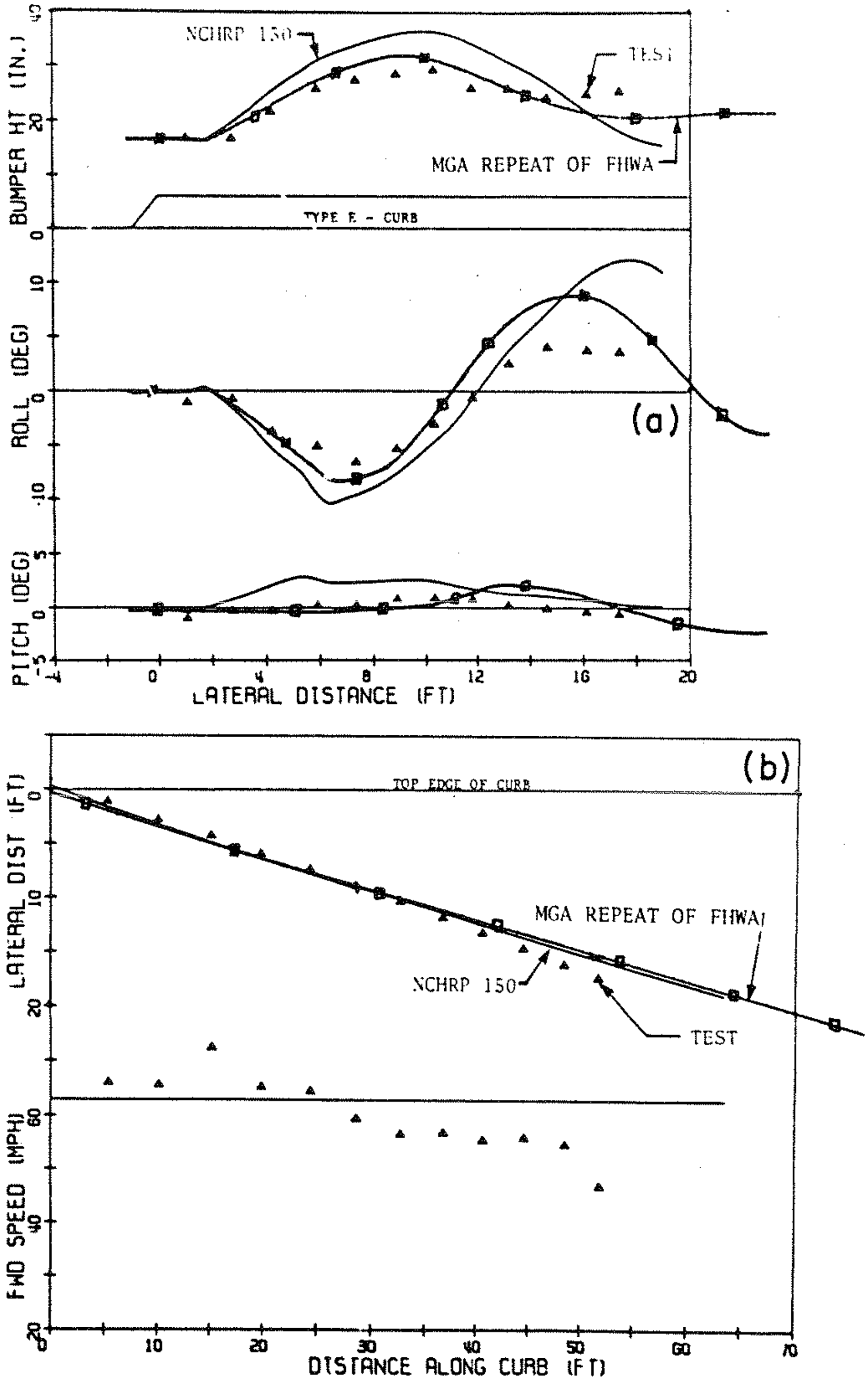


Figure 59 CURB TYPE E, TEST N-10 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

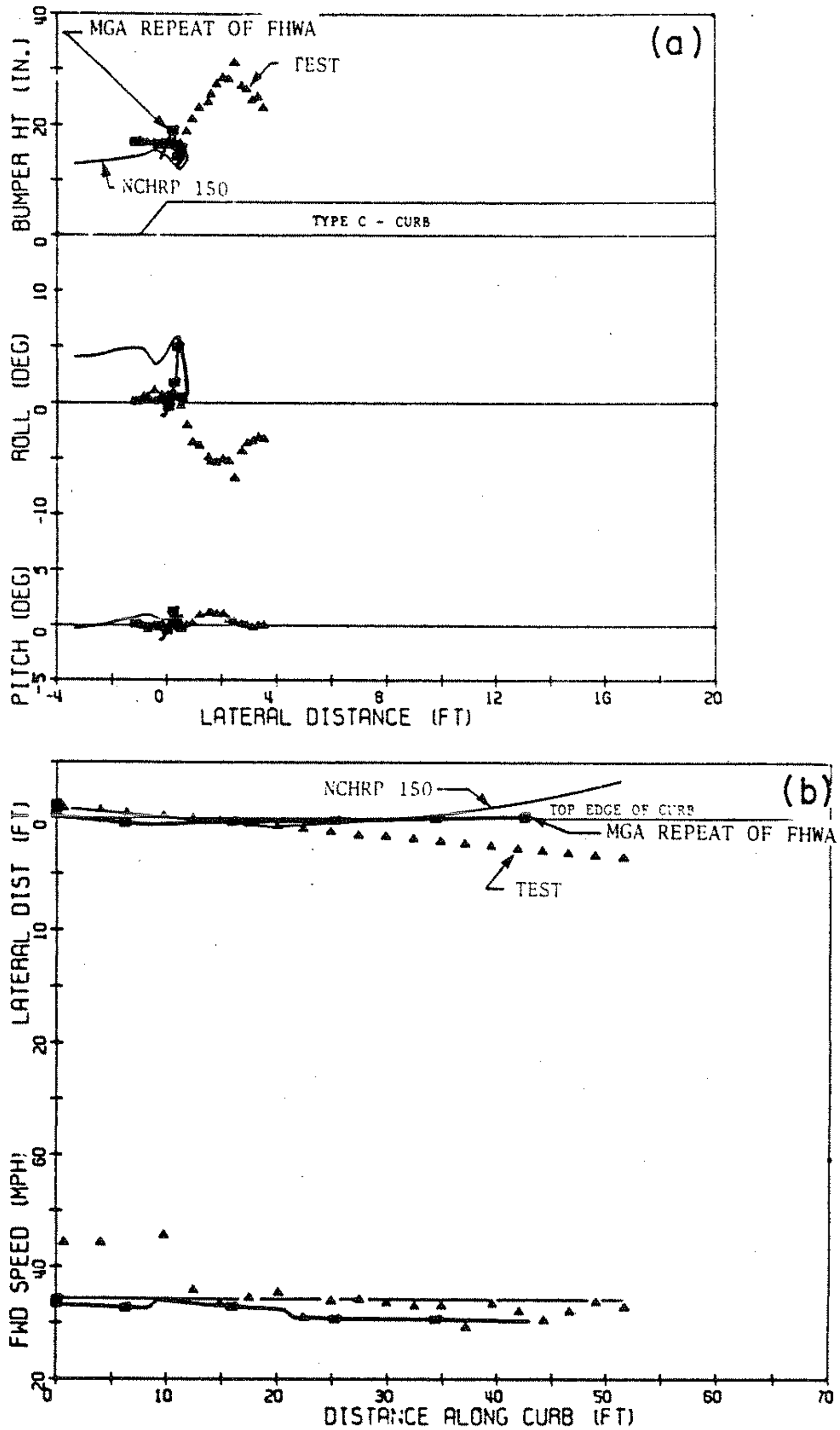


Figure 60 CURB TYPE C, TEST N-11 AT 30-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

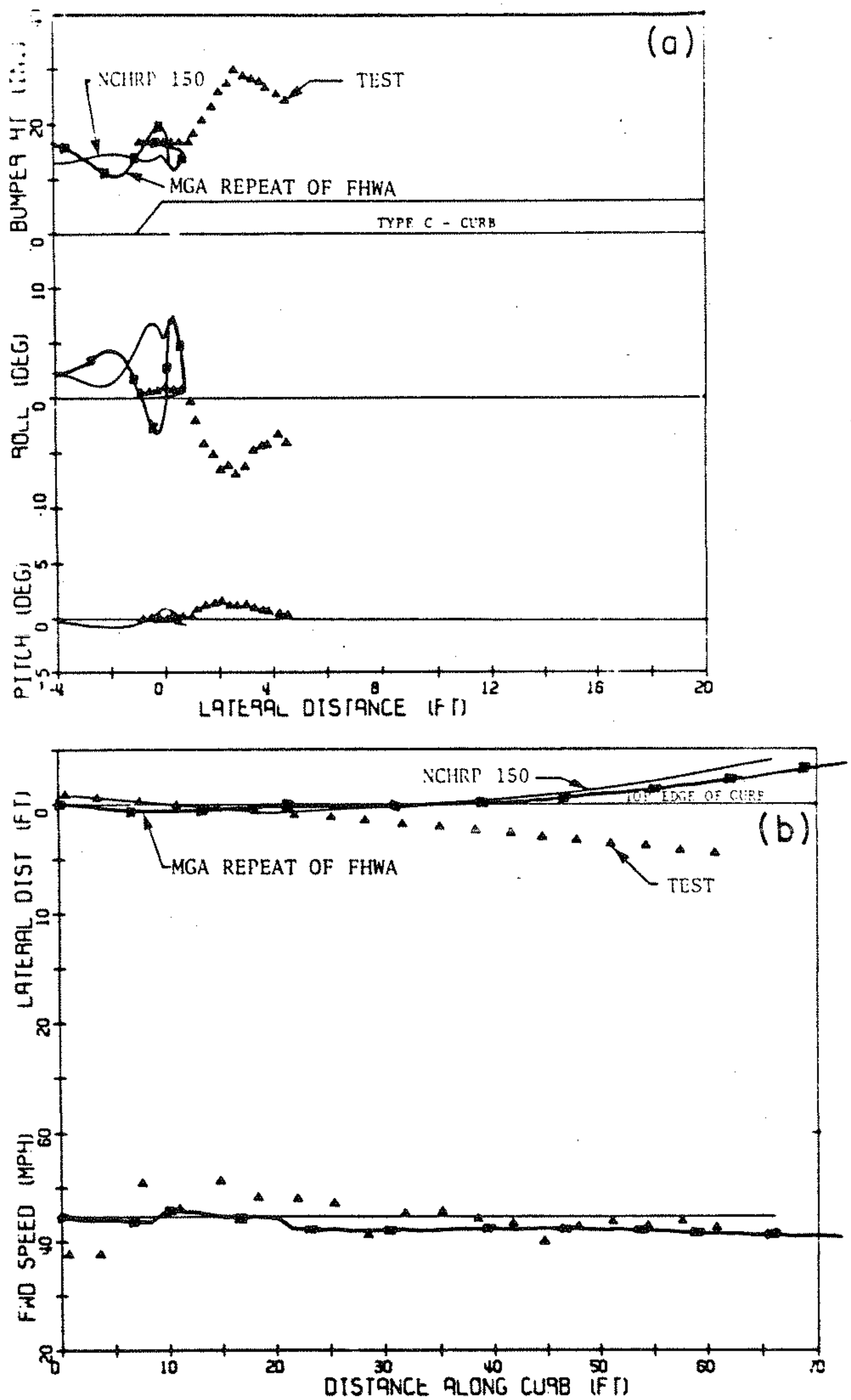


Figure 61 **CURB TYPE C, TEST N-12 AT 45-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH**

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

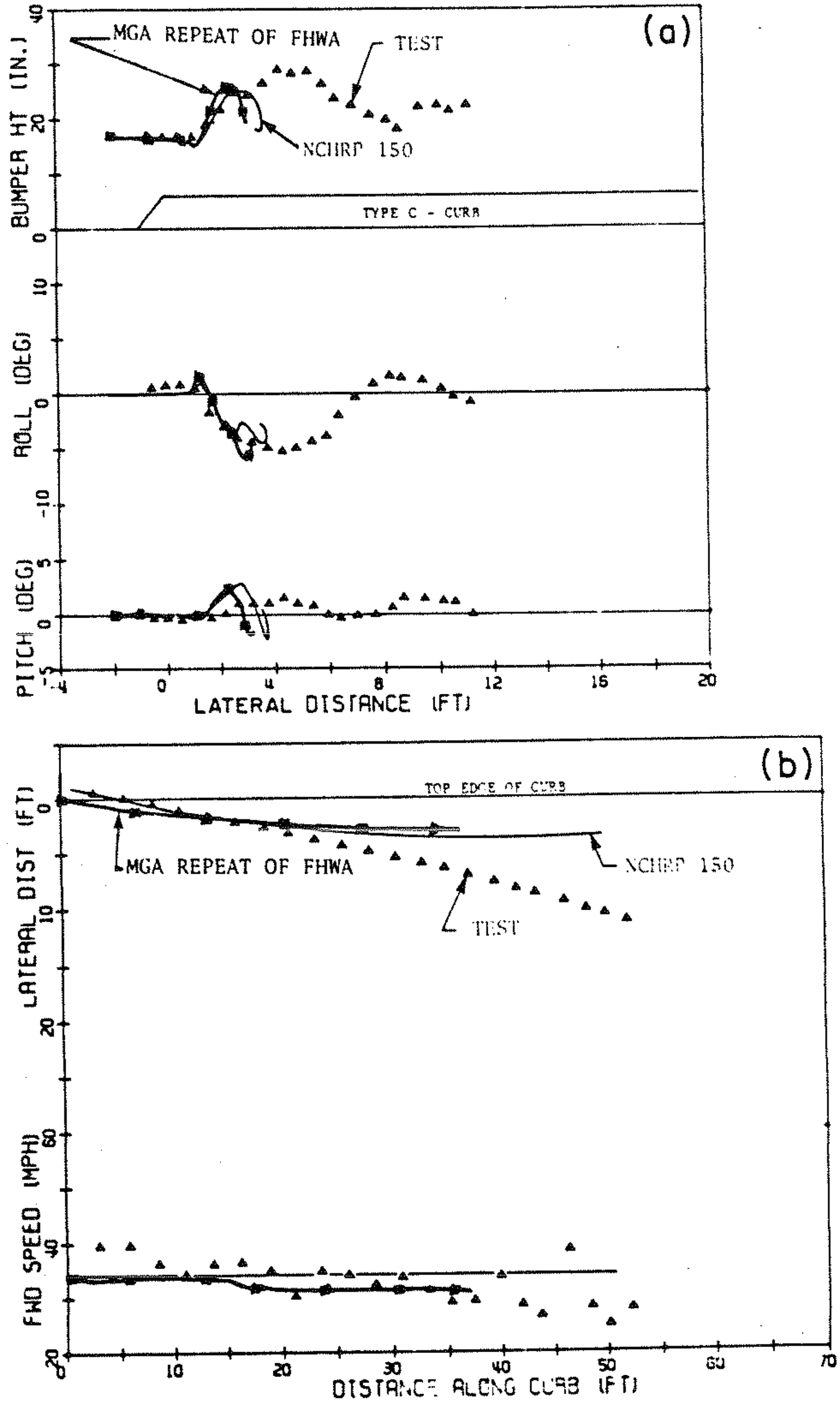


Figure 62 **CURB TYPE C, TEST N-13 AT 30-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH**

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

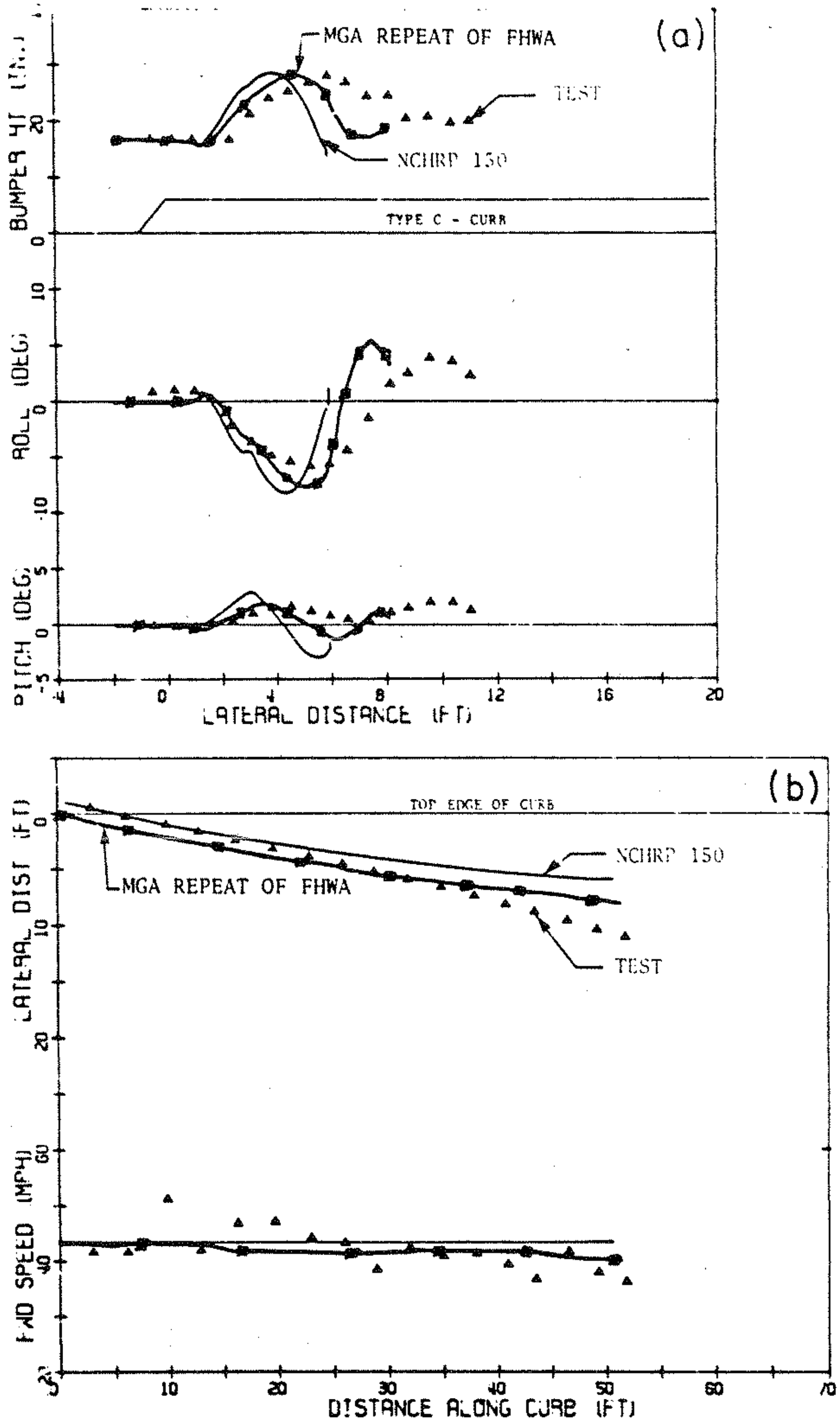


Figure 63 CURB TYPE C, TEST N-14 AT 45-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

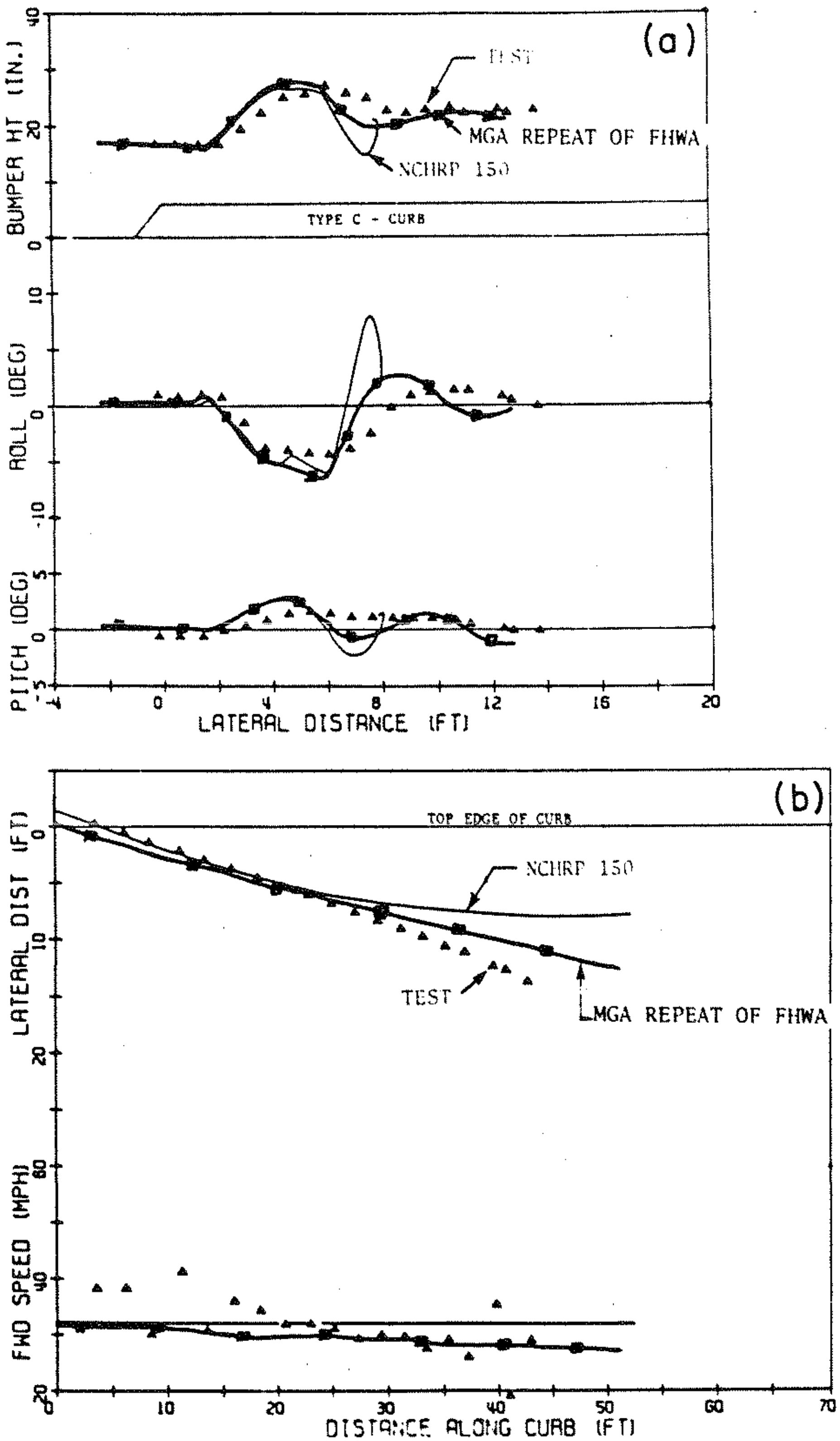


Figure. CURB TYPE C, TEST N-15 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

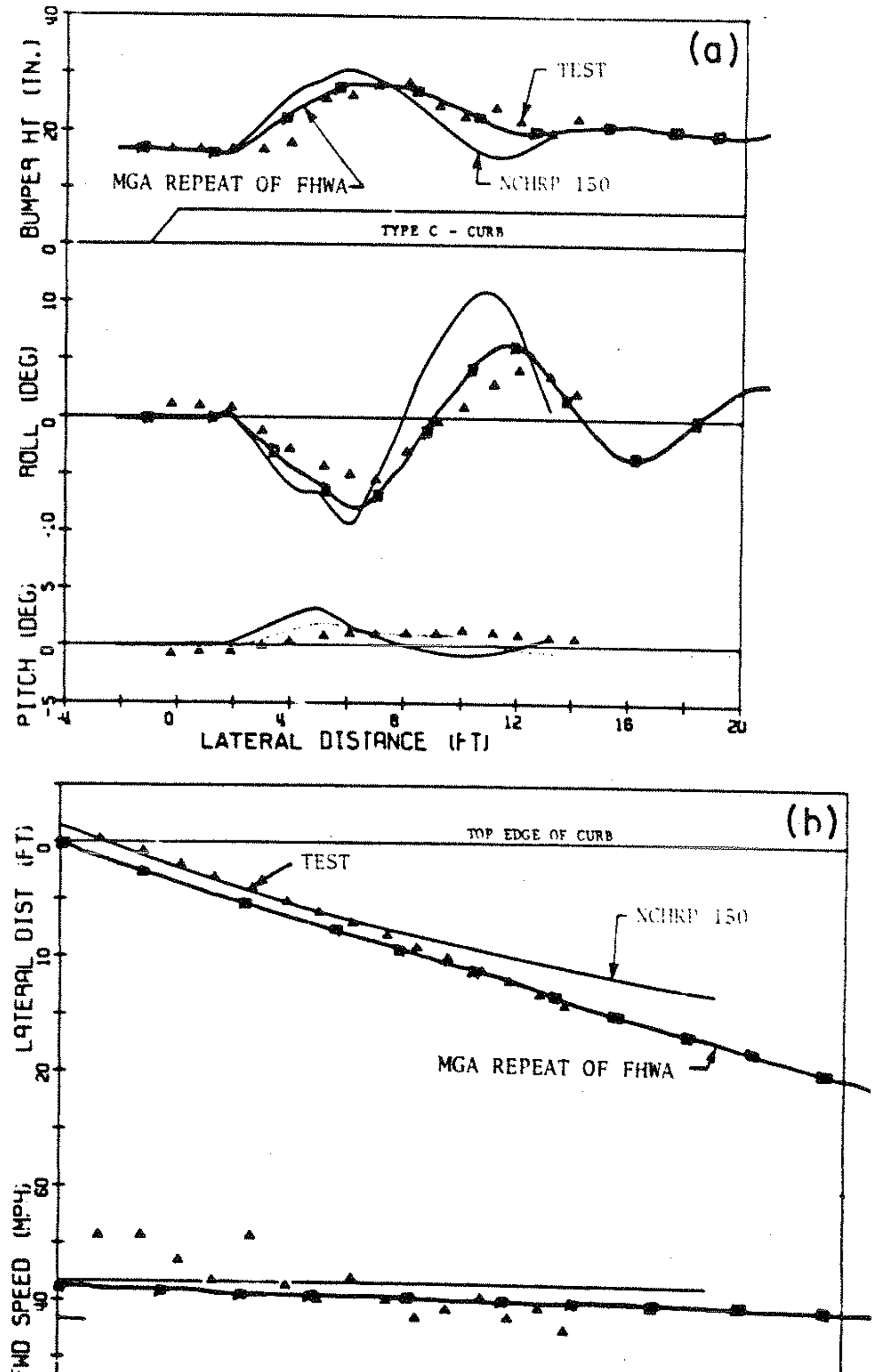


Figure 65 CURB TYPE C, TEST N-16 AT 45-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

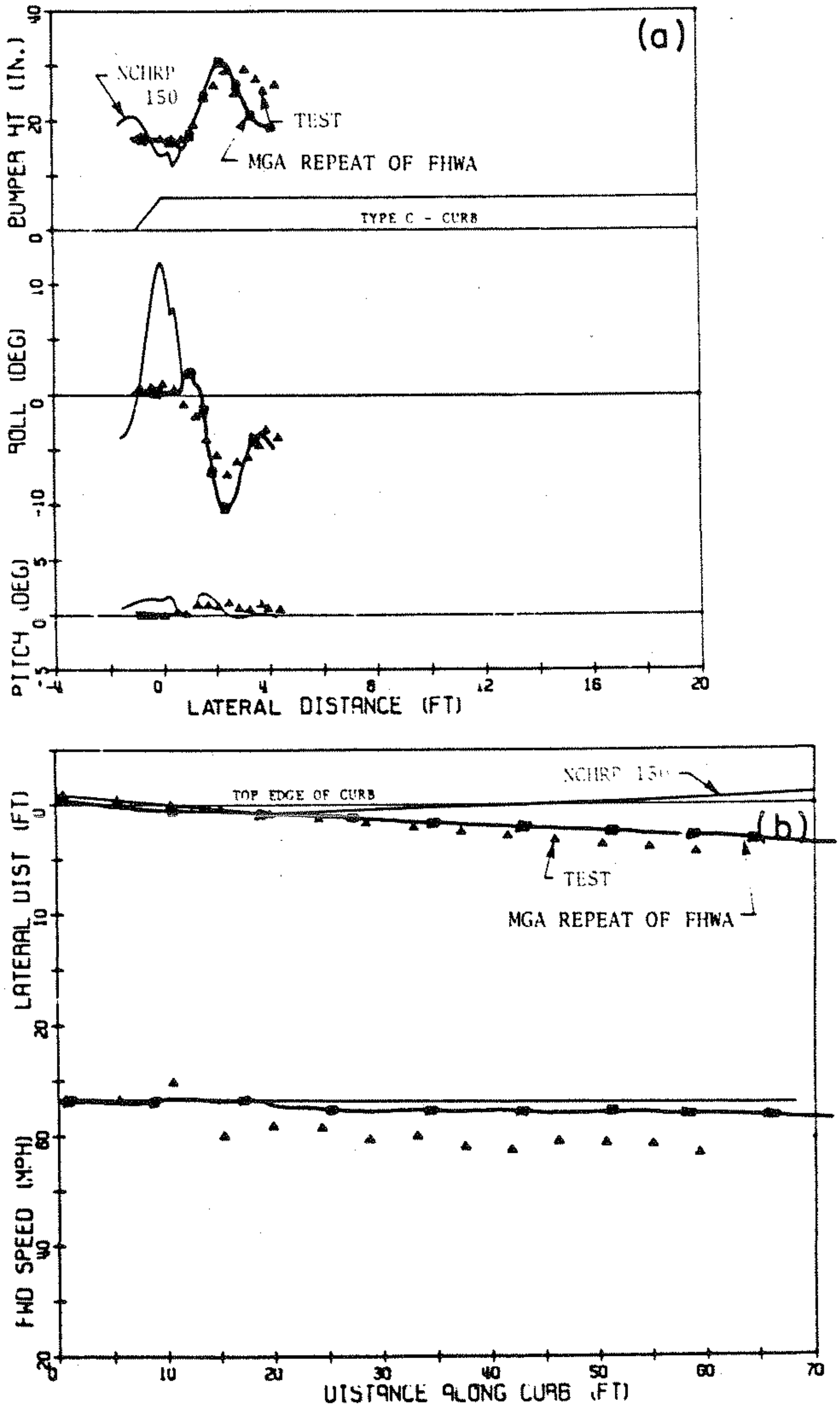
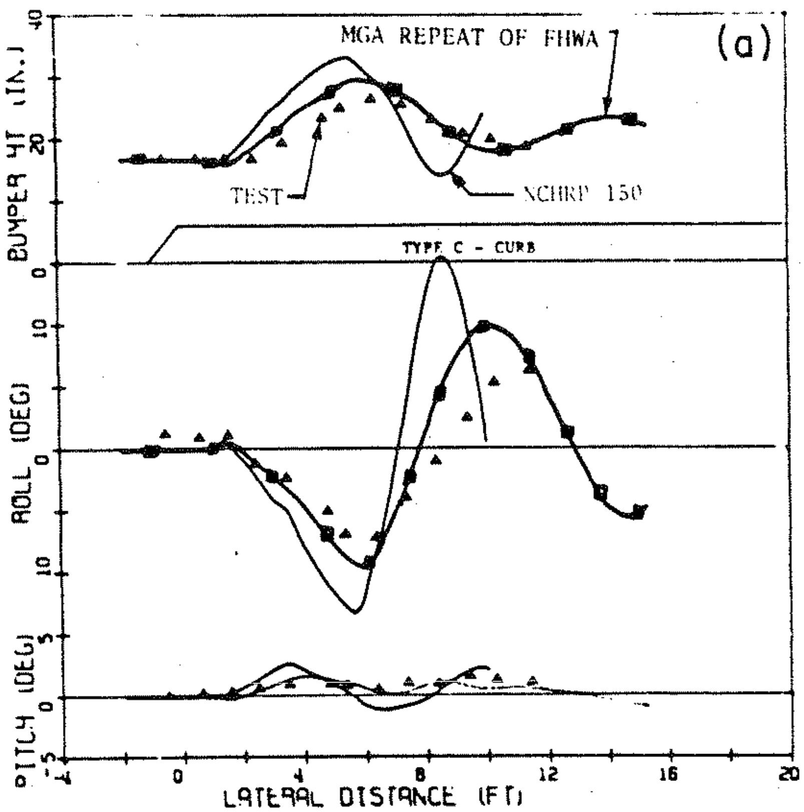


Figure 66 CURB TYPE C, TEST N-17 AT 60-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h



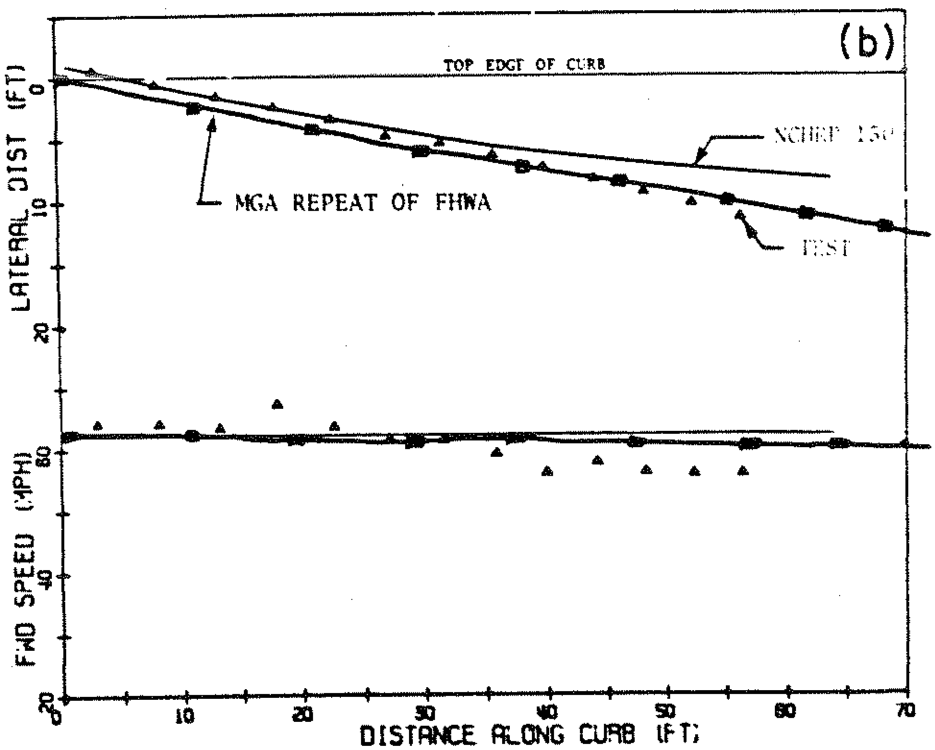


Figure 67 CURB TYPE C, TEST N-18 AT 60-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

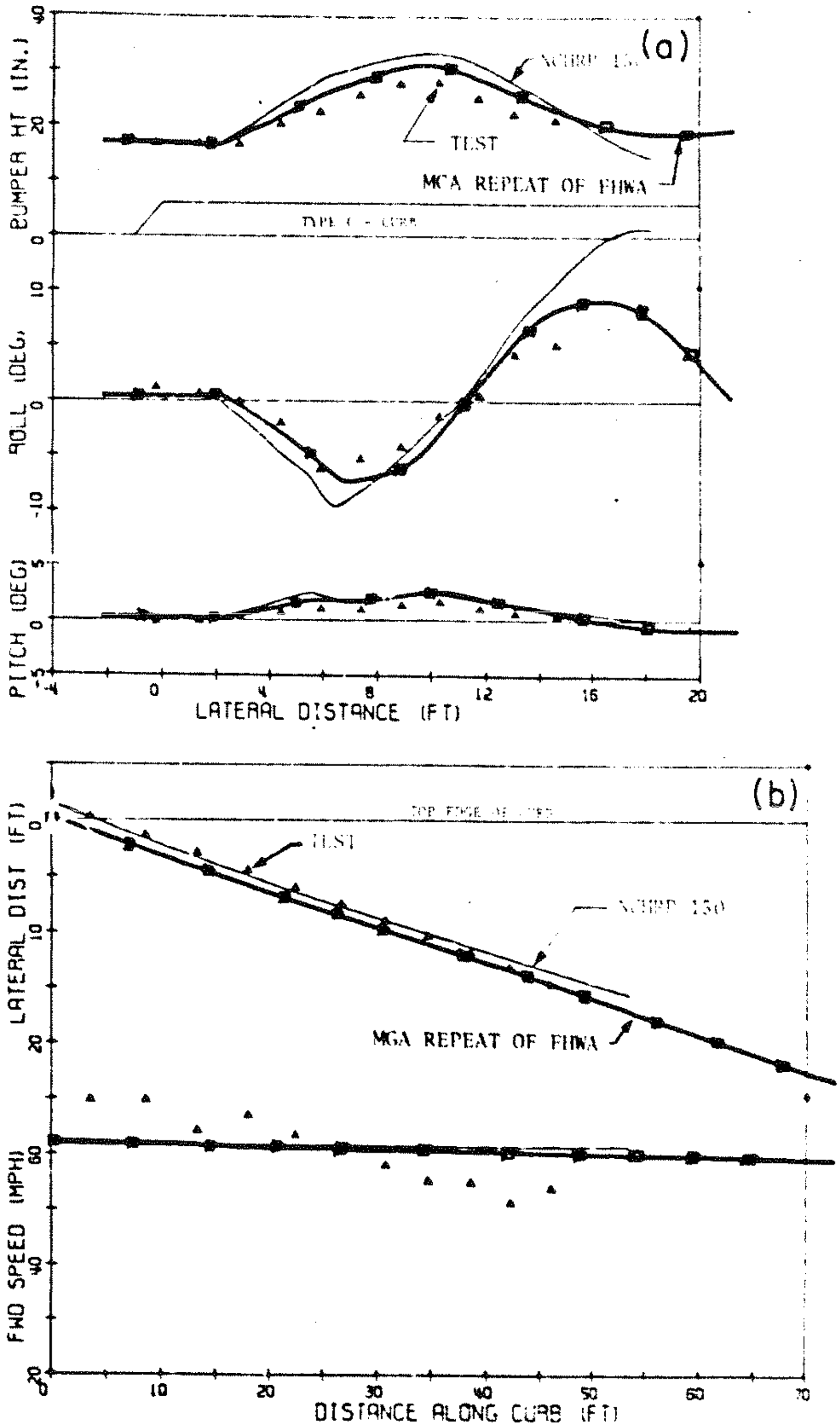


Figure 68 CURB TYPE C, TEST N-19 AT 60-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

APPENDIX C

MGA HVOSM SENSITIVITY STUDY

Figures 69 through 95 show the HVOSM results from the sensitivity study conducted by MGA. The results are plotted against the corresponding NCHRP 150 full-scale results (denoted by the individual triangles and labeled "TEST") and the MGA duplication of the MCI simulation runs (denoted by the solid line labeled "MGA REPEAT OF MCI") for comparison purposes. The input parameter changed is given as a plot title, and the change or changes made are noted in legend fashion. Each figure is composed of two parts. Part (a) plots vehicle pitch angle, roll angle, and bumper height with respect to lateral distance behind the curb. Part (b) shows vehicle path and speed with respect to distance along the curb from point of impact.

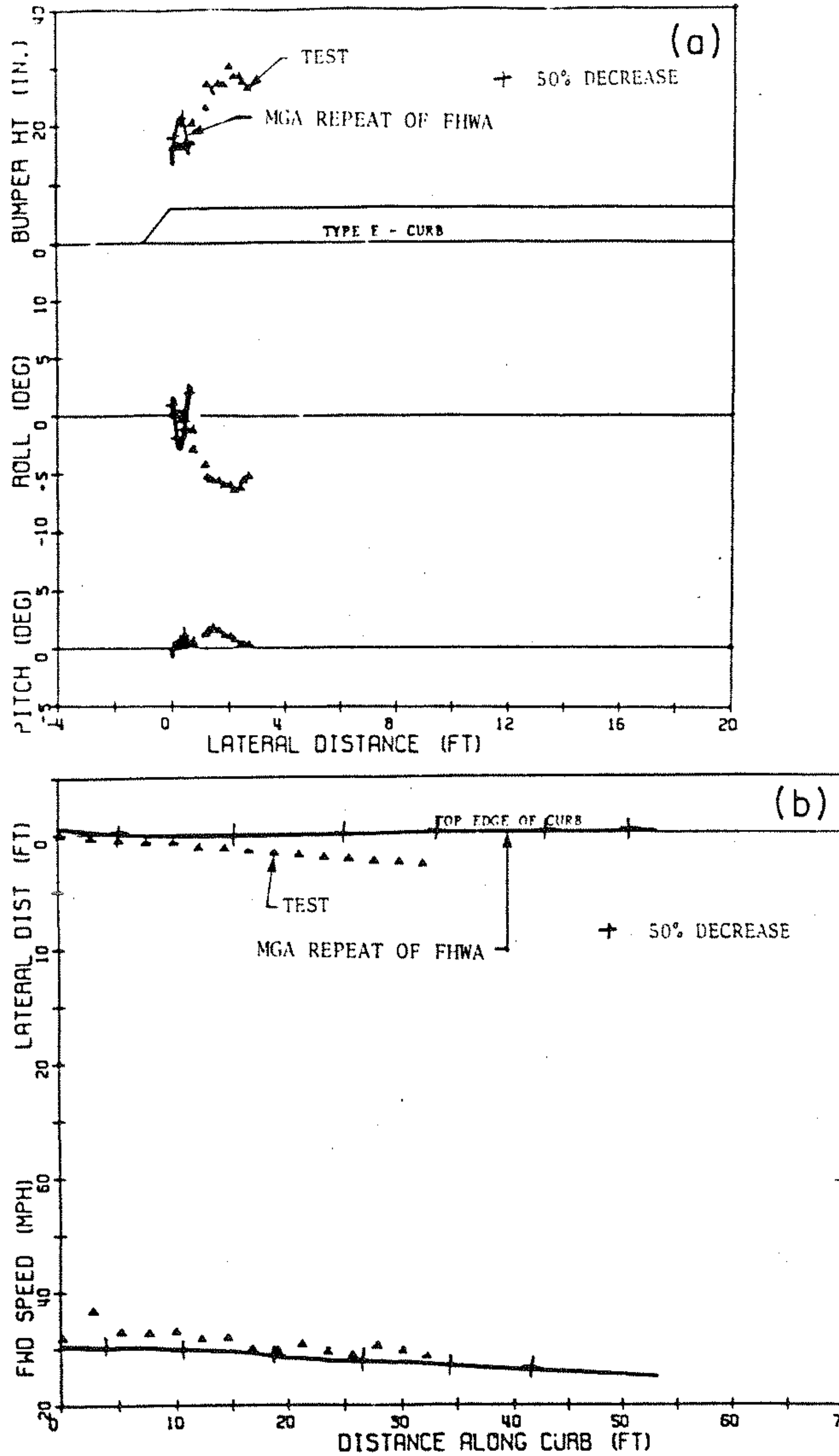


Figure 69 TIRE BOTTOMING DEFLECTION CURB TYPE E, TEST N-2 AT 30 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

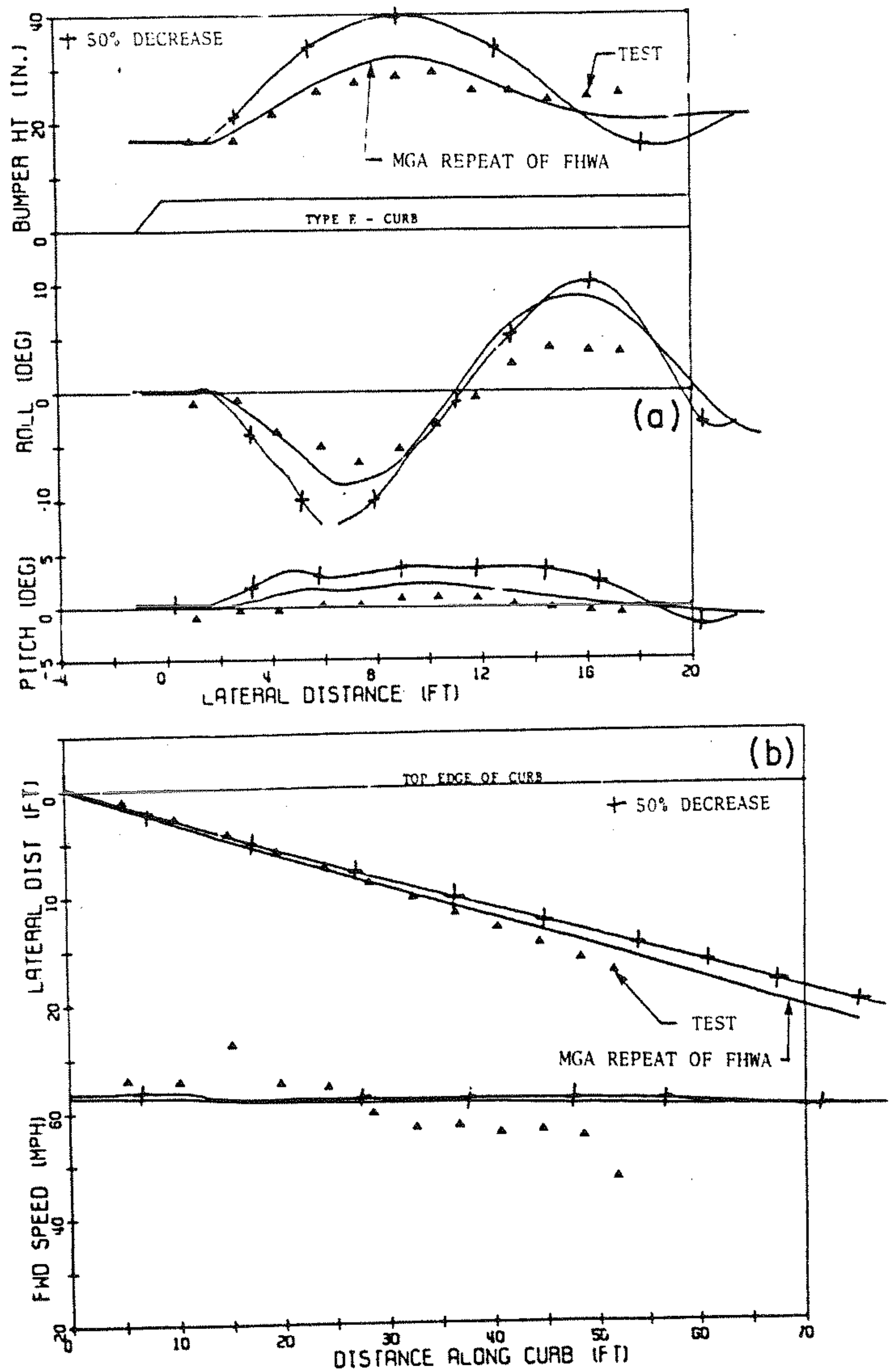


Figure 70 TIRE BOTTOMING DEFLECTION CURB TYPE E, TEST N-10 AT 60 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

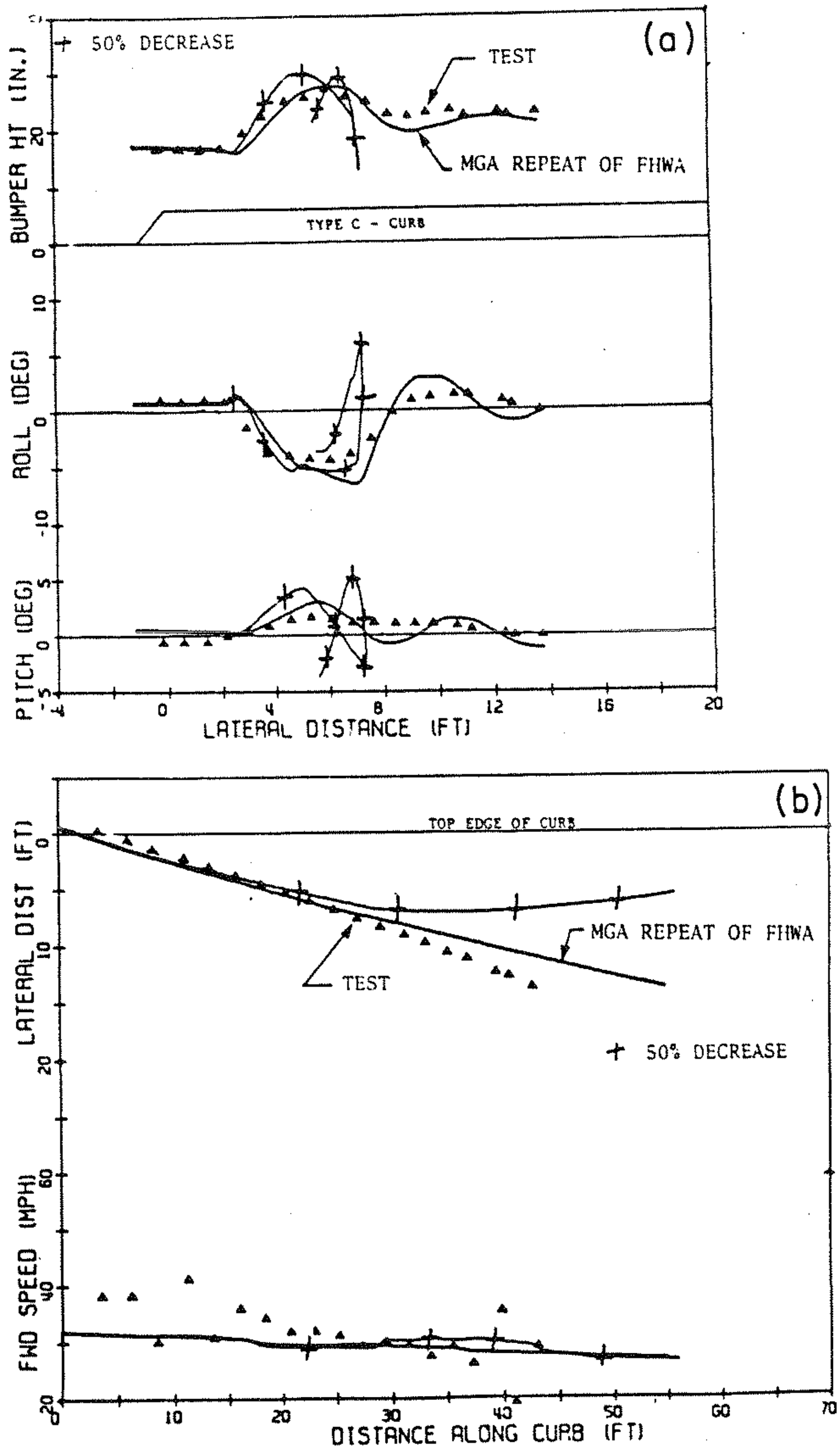


Figure 71 TIRE BOTTOMING DEFLECTION CURB TYPE C, TEST N-15 AT 30 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

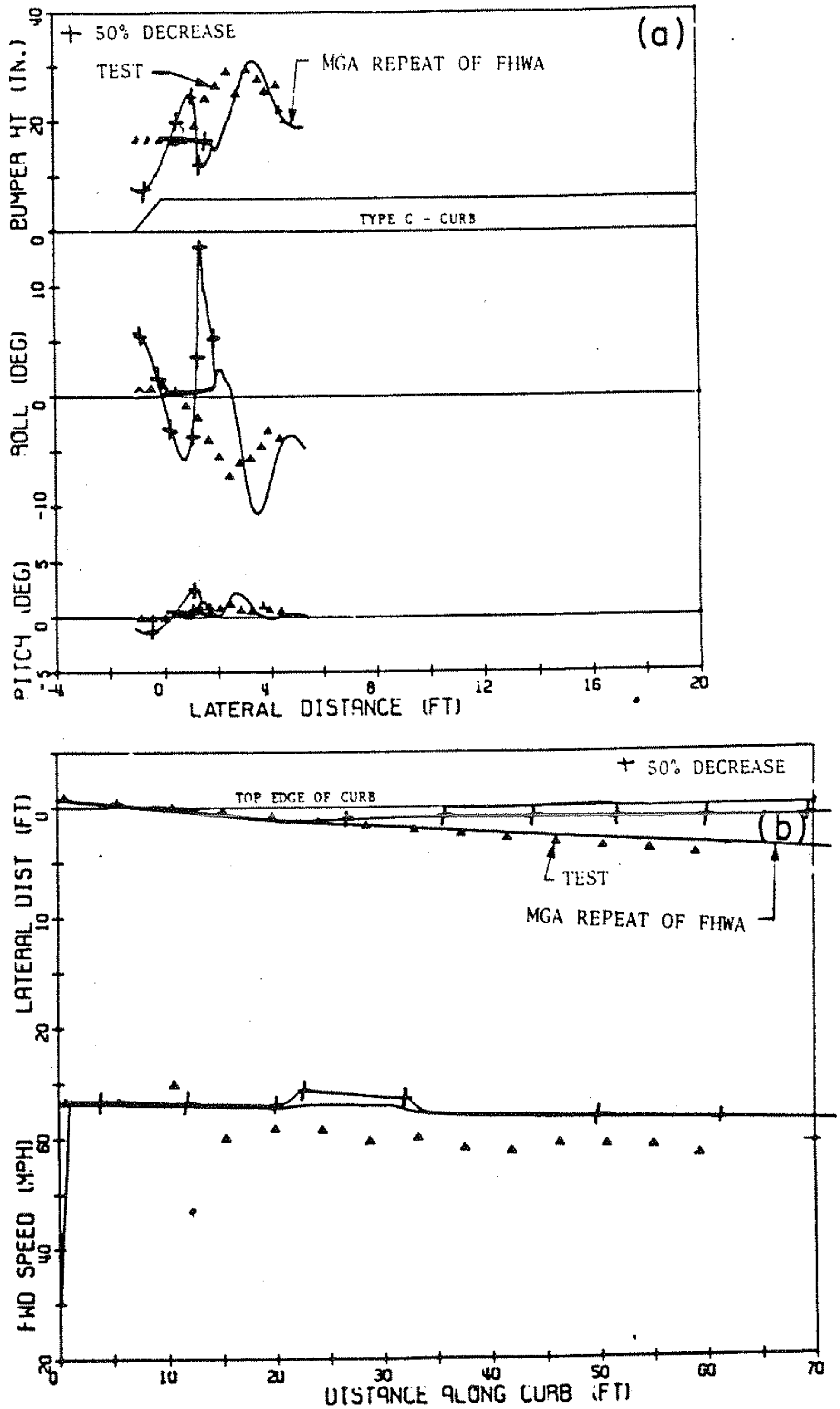


Figure 72 TIRE BOTTOMING DEFLECTION CURB TYPE C, TEST N-17 AT 60 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

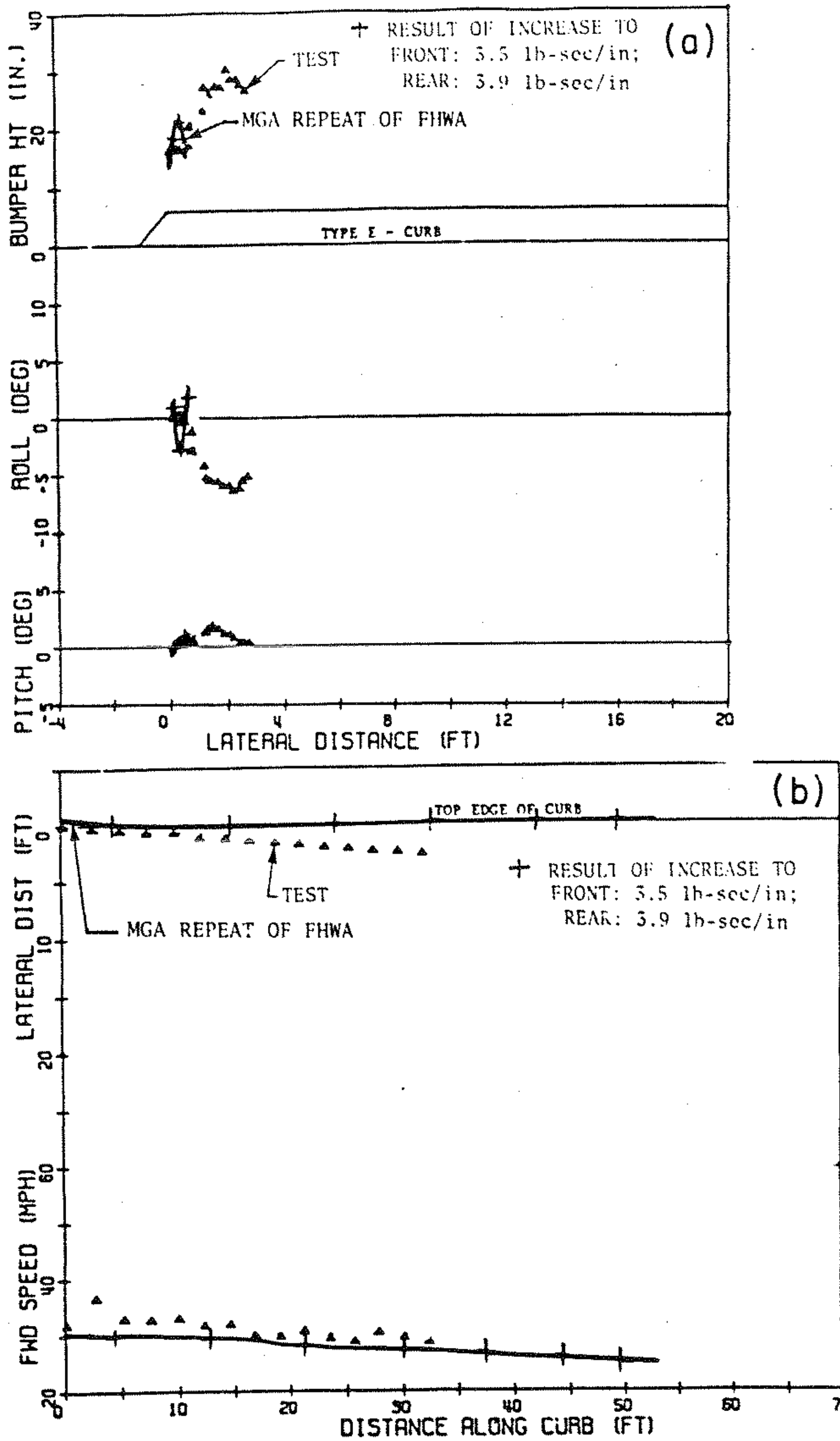


Figure 73 SUSPENSION DAMPING CURB TYPE E, TEST N-2 AT 30 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

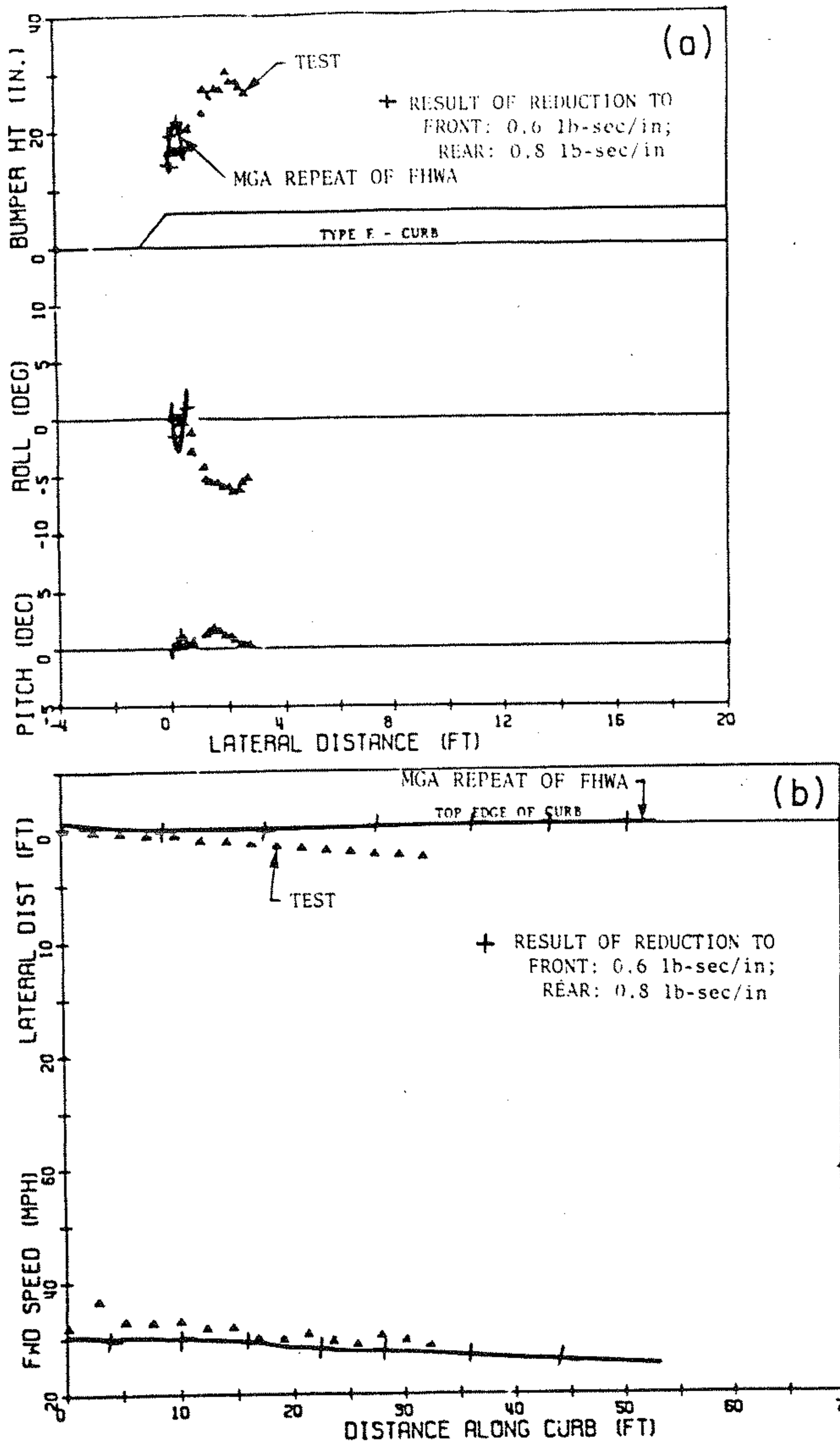


Figure 74 SUSPENSION DAMPING CURB TYPE E, TEST N-2 AT 30 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

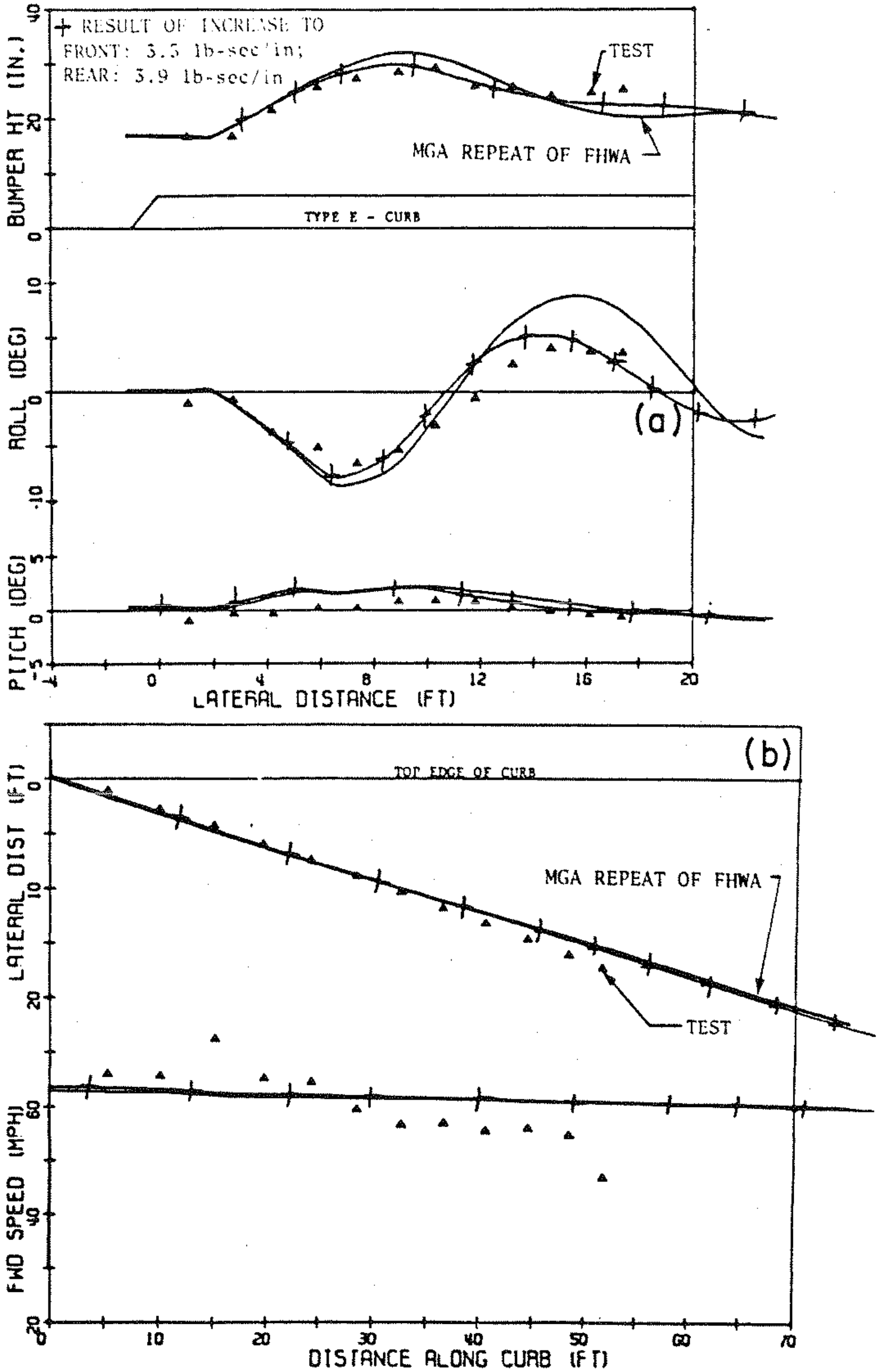


Figure 75 SUSPENSION DAMPING CURB TYPE E, TEST N-10 AT 60 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

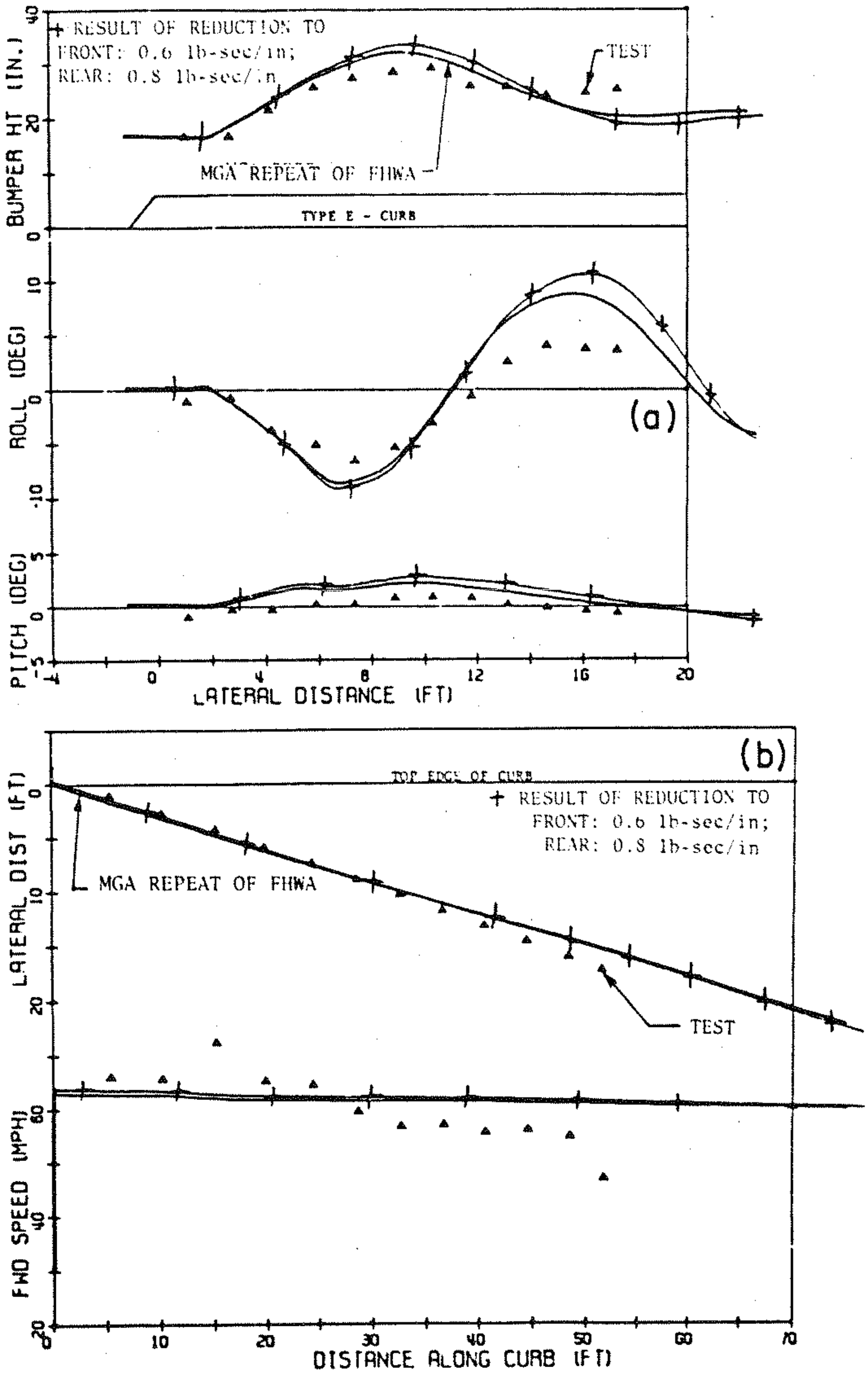


Figure 76 SUSPENSION DAMPING CURB CURB TYPE E, TEST N-10 AT 60 MPH AND 20 DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

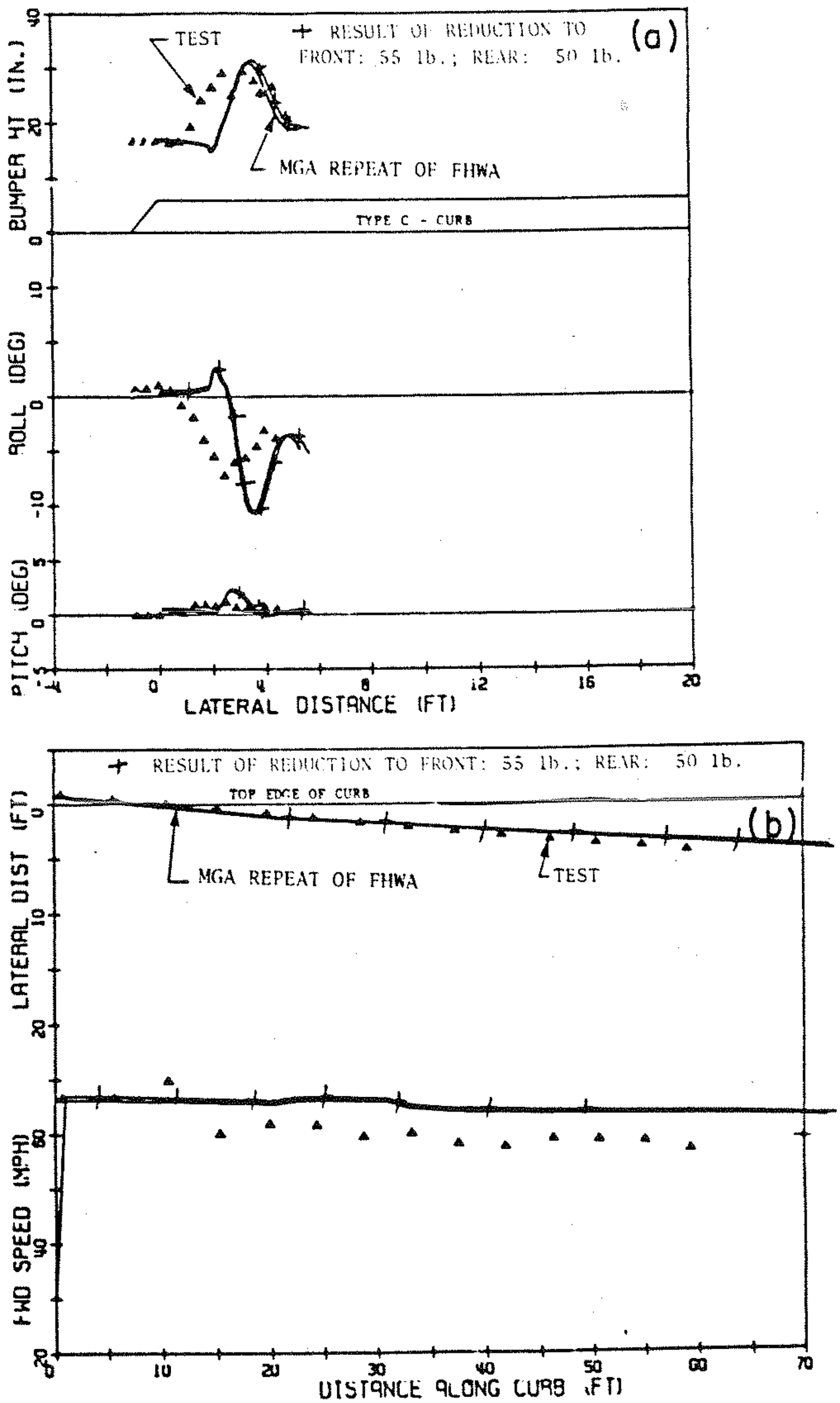


Figure 77 SUSPENSION FRICTION CURB TYPE C, TEST N-17 AT 60 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

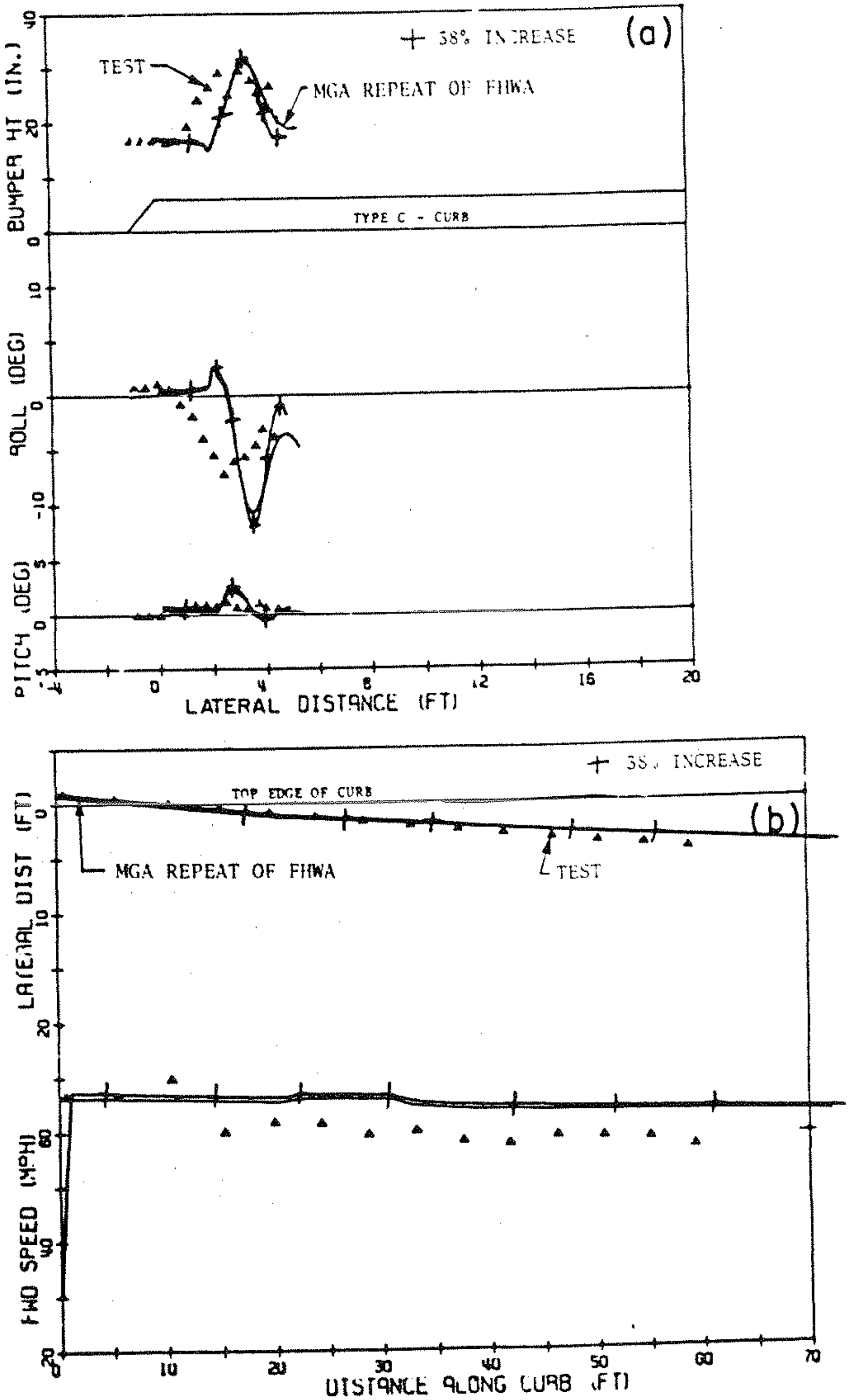


Figure 78 REAR AXLE ROLL INERTIA CURB TYPE C, TEST N-17 AT 60 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

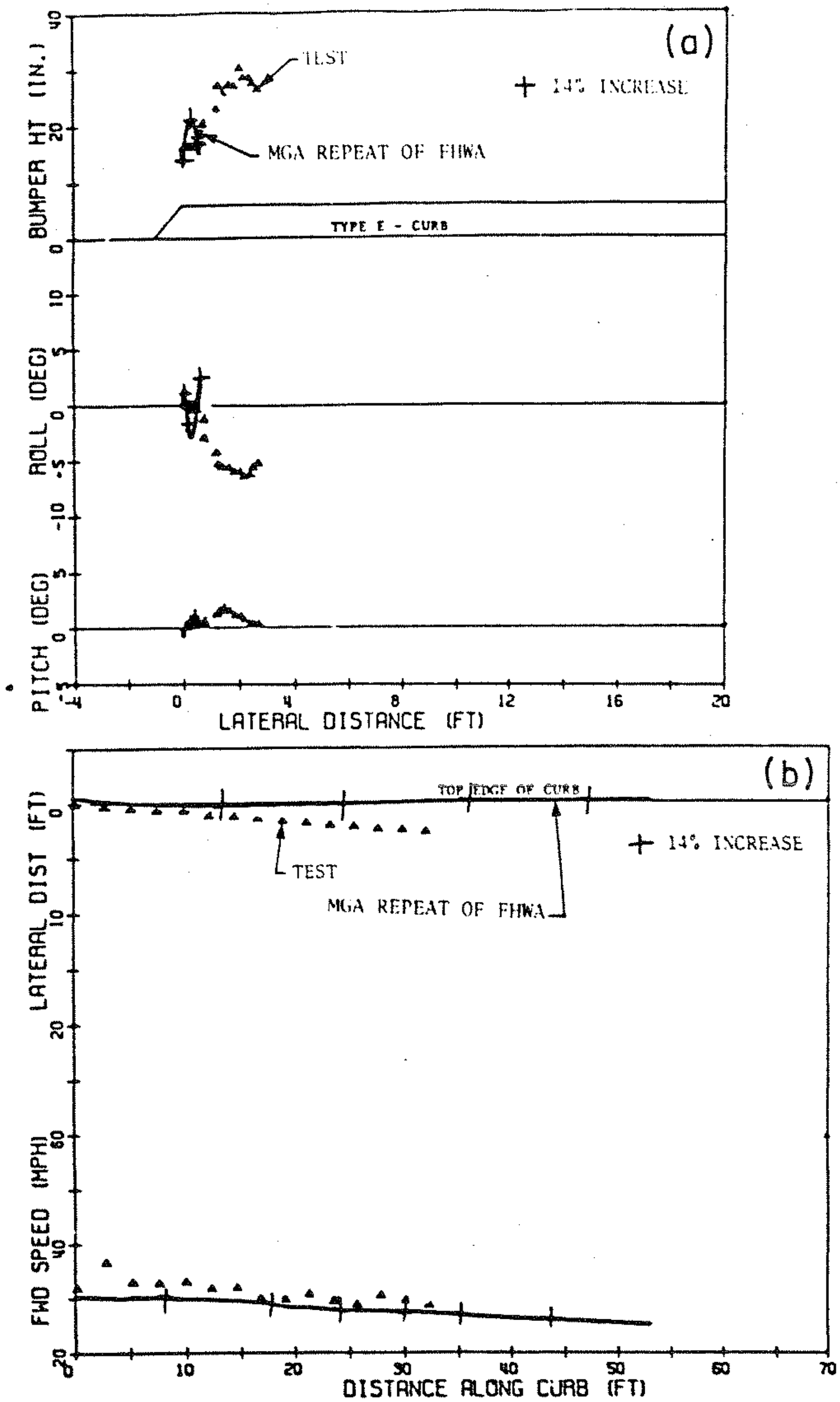


Figure 79 SPRUNG MASS PTICH INERTIA CURB TYPE E, TEST N-2 AT 30 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

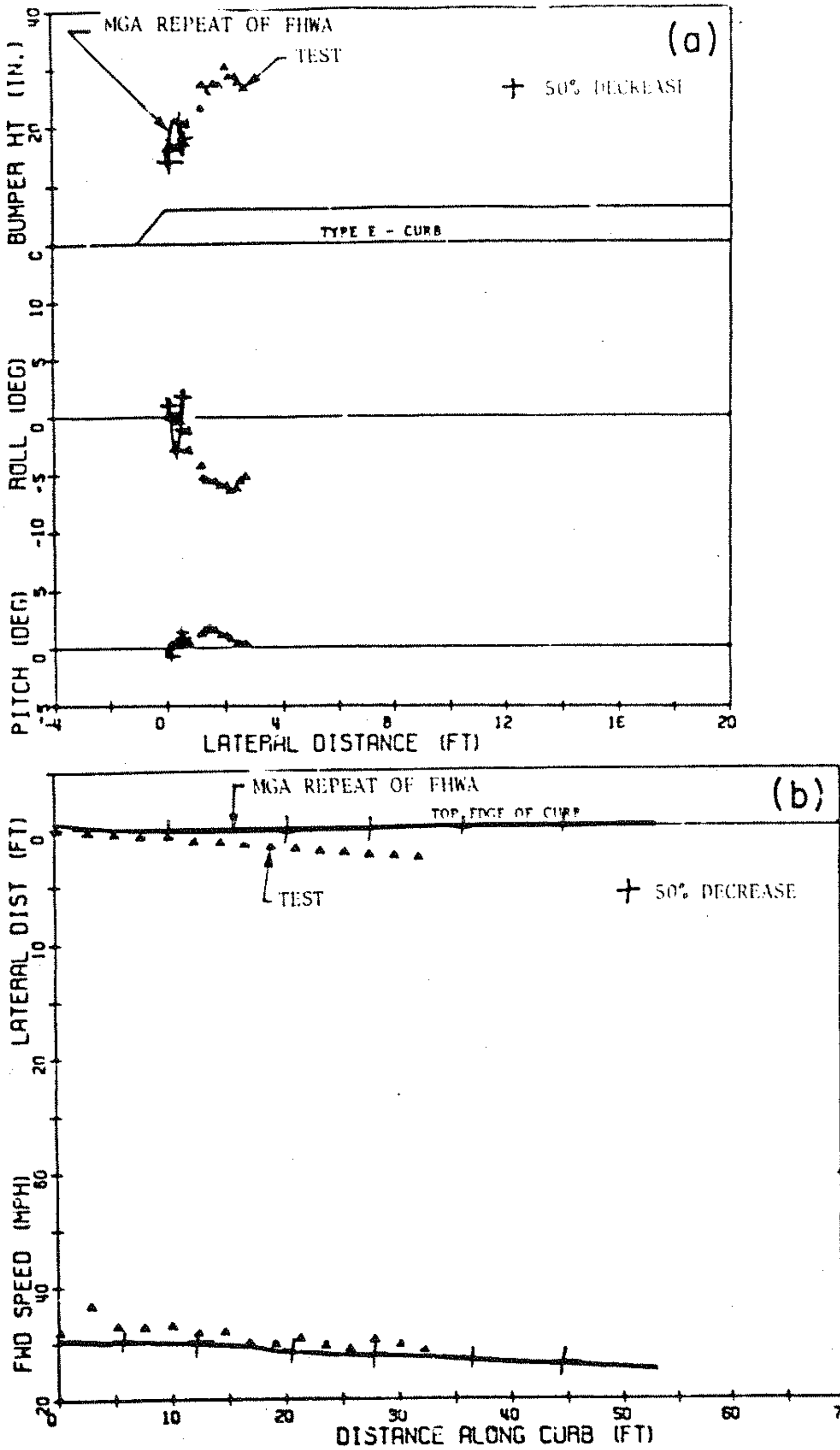


Figure 80 SPRUNG MASS PITCH INERTIA CURB TYPE E, TEST N-2 AT 30 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

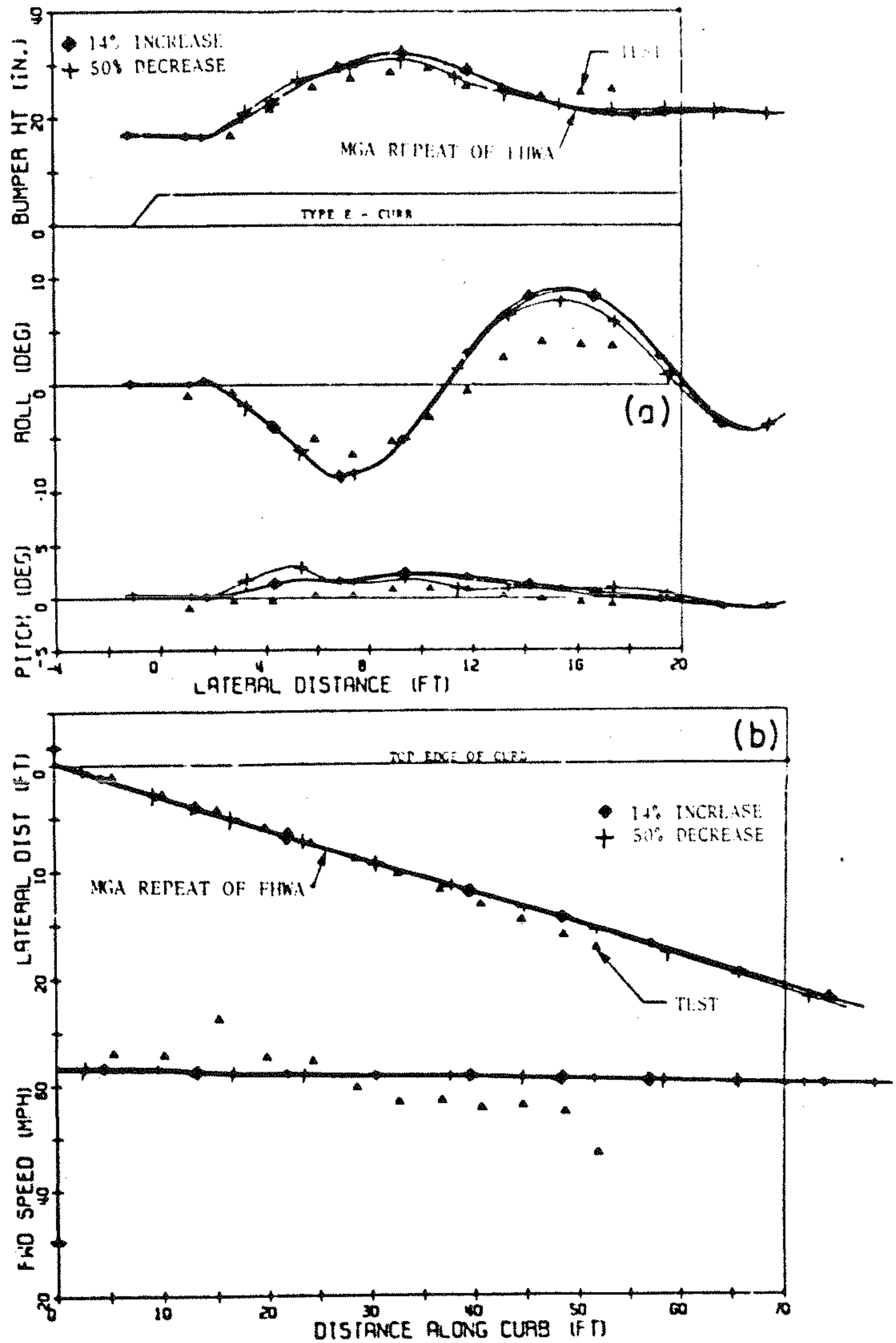
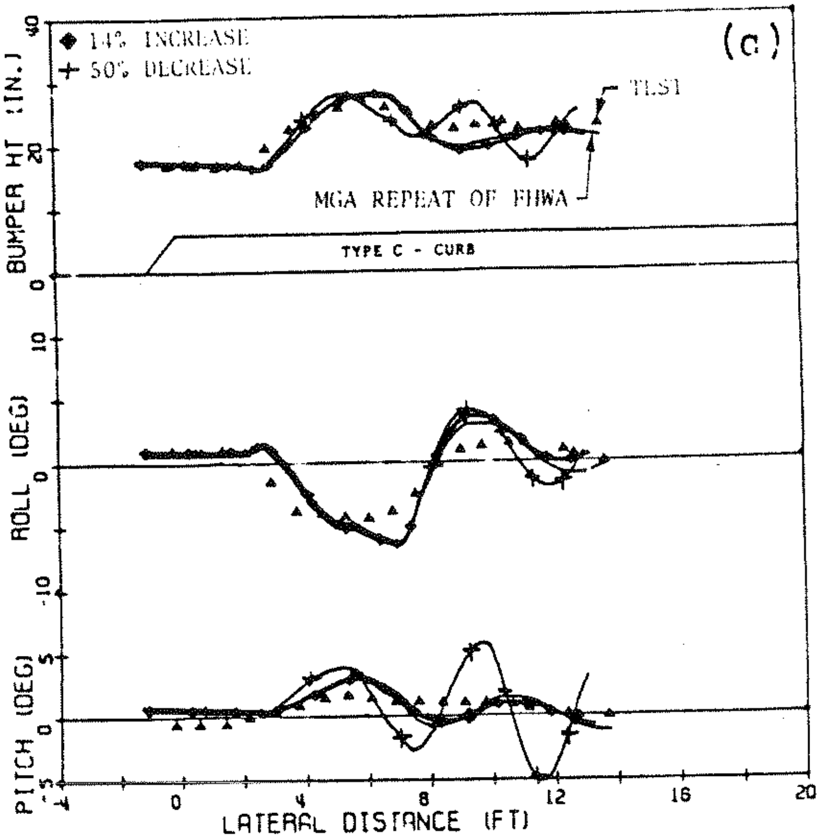


Figure 81 SPRUNG MASS PITCH INERTIA CURB TYPE E, TEST N-10 AT 60 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h



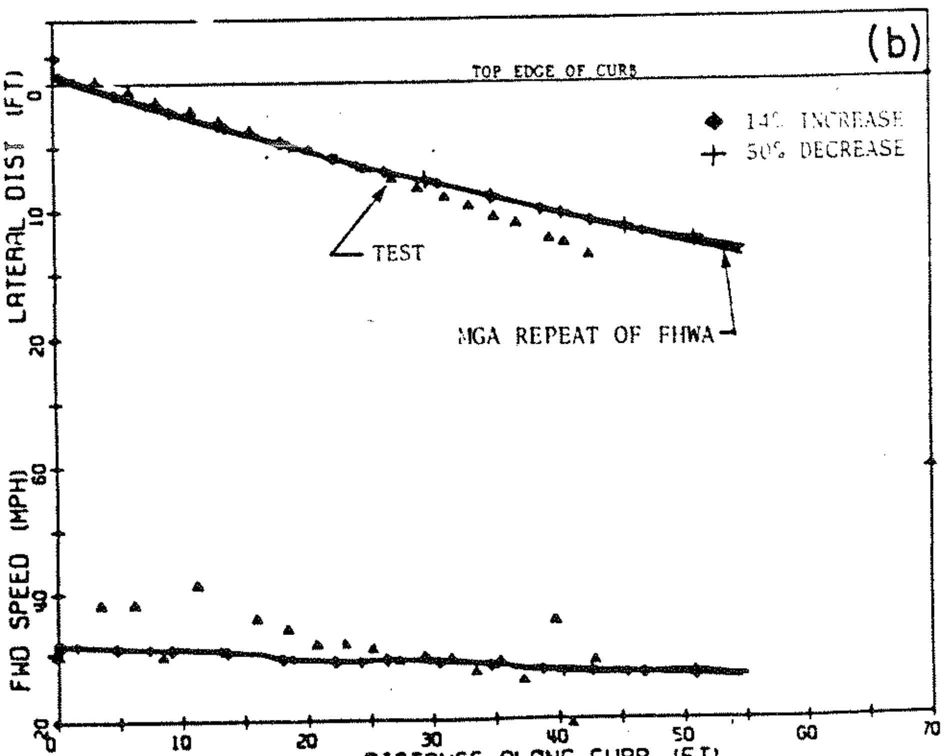


Figure 82 SPRUNG MASS PITCH INERTIA CURB TYPE C, TEST N-15 AT 30 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

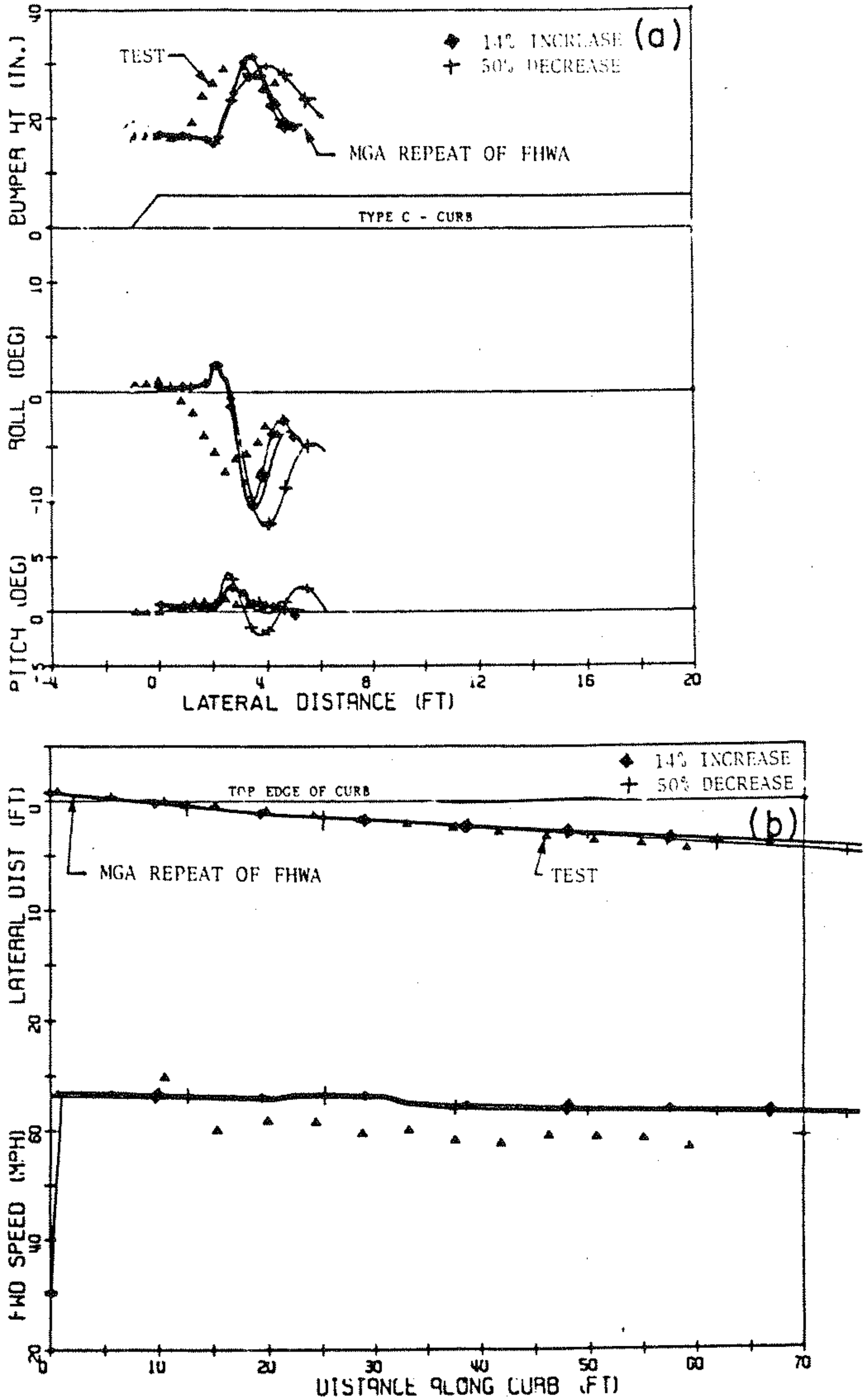


Figure 83 SPRUNG MASS PITCH INERTIA CURB TYPE C, TEST N-17 AT 60 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

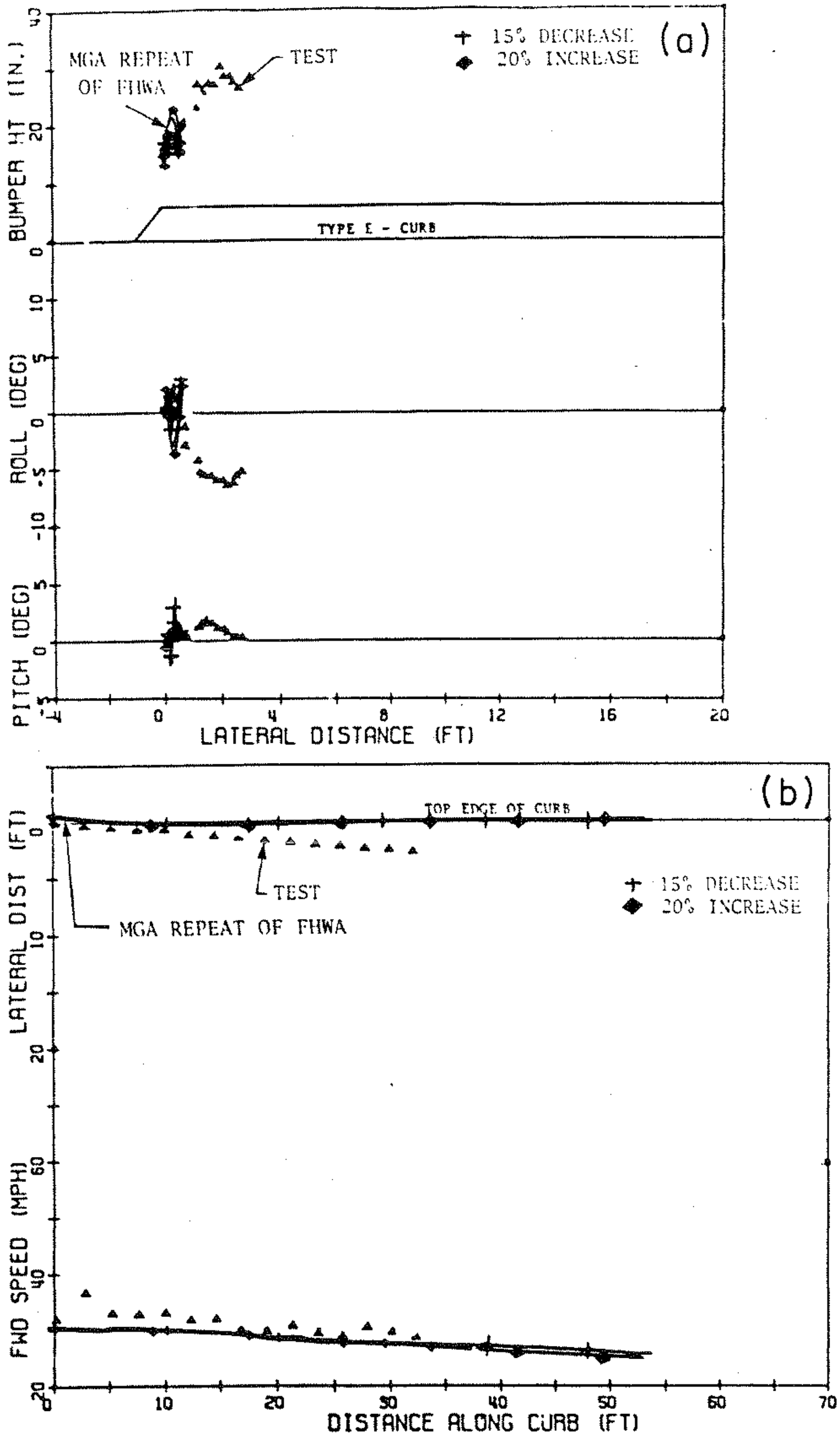


Figure 84. SPRUNG MASS YAW INERTIA CURB TYPE E, TEST N-2 AT 30 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

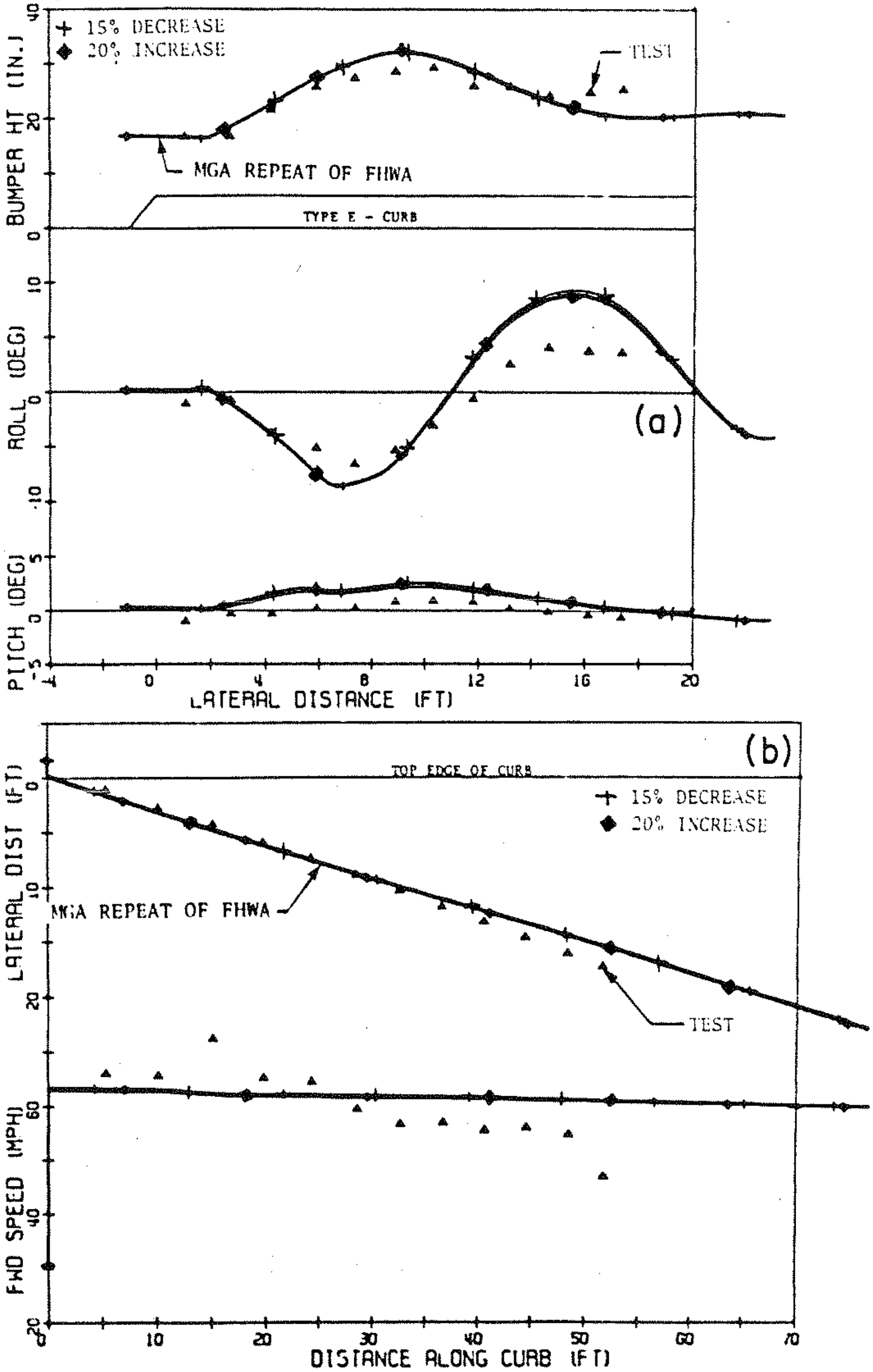


Figure 85 SPRUNG MASS YAW INERTIA CURB TYPE E, TEST N-10 AT 30 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

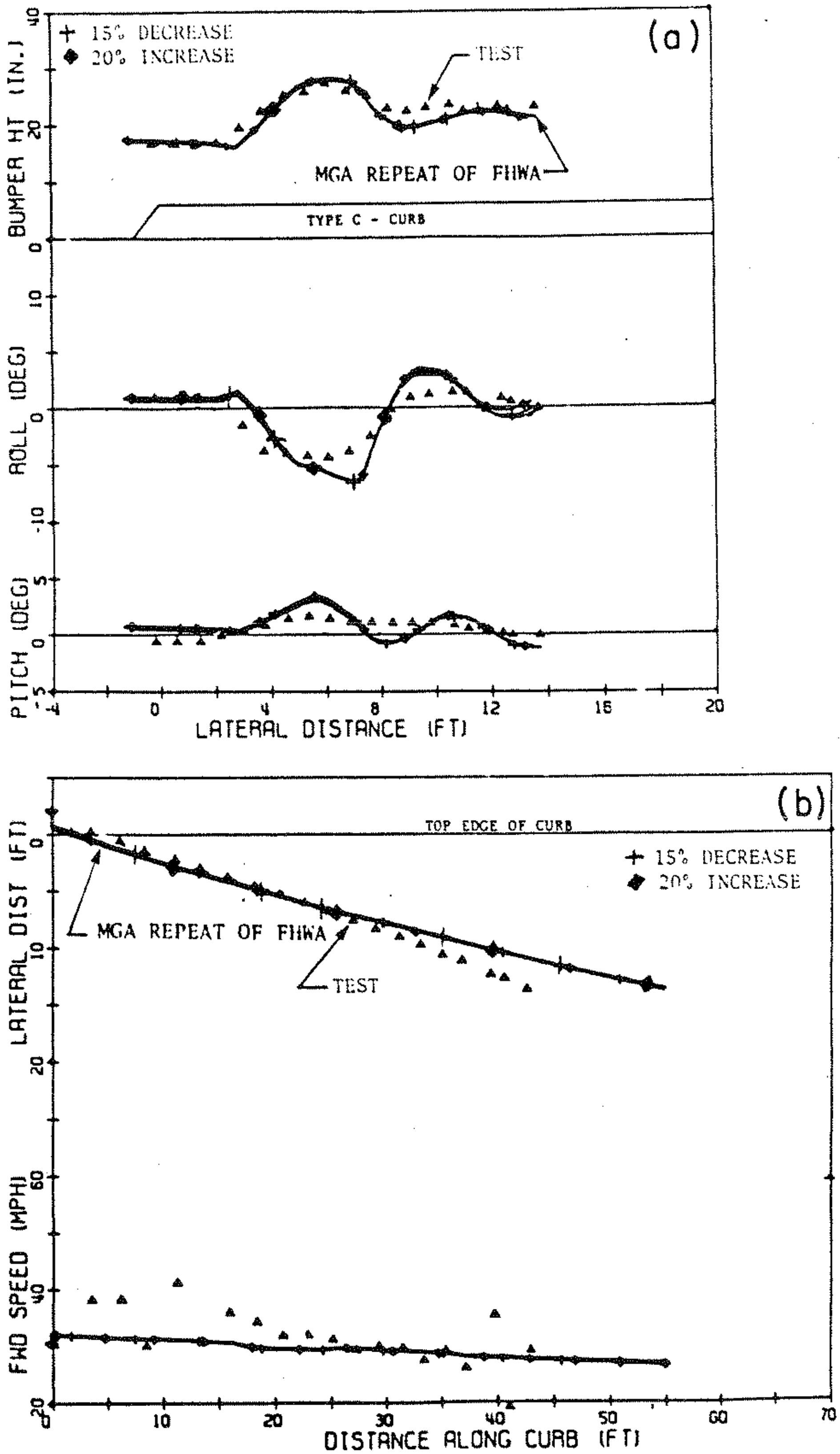


Figure 86 SPRUNG MASS YAW INERTIA CURB TYPE C, TEST N-15 AT 30 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

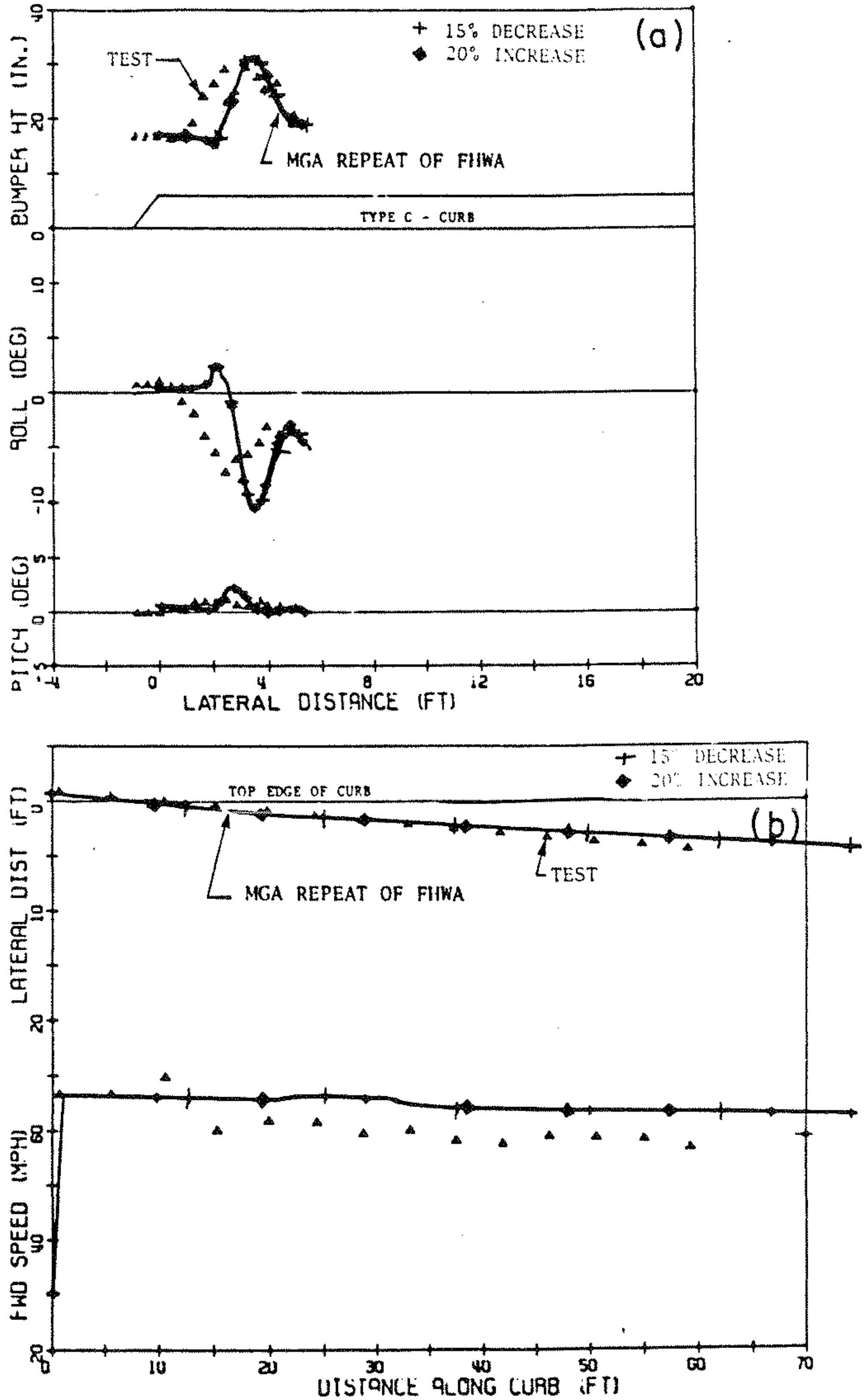


Figure 87 SPRUNG MASS YAW INERTIA CURB TYPE C, TEST N-17 AT 60 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

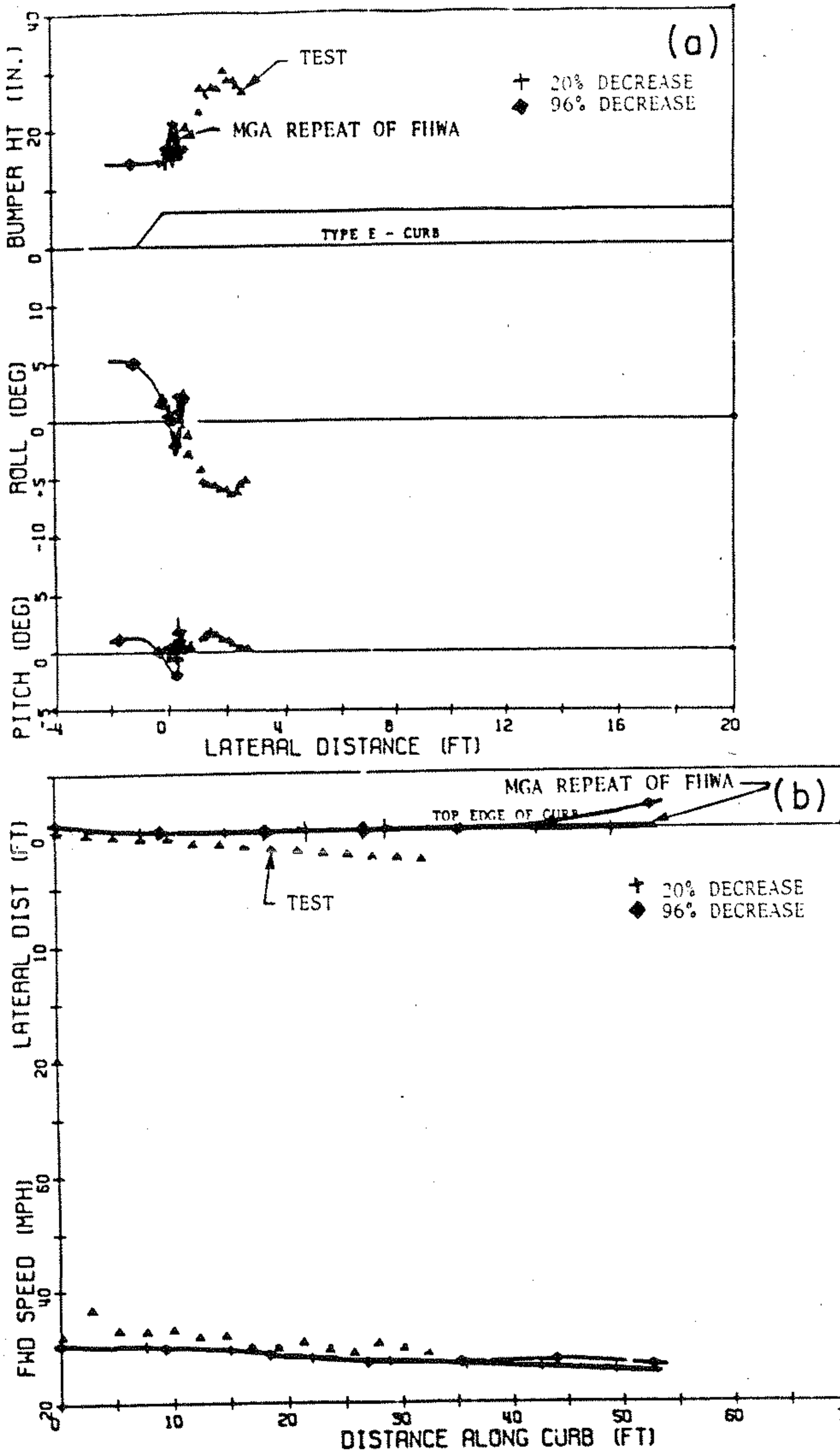


Figure 88 STEERING SYSTEM FRICTION CURB TYPE E, TEST N-2 AT 30 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

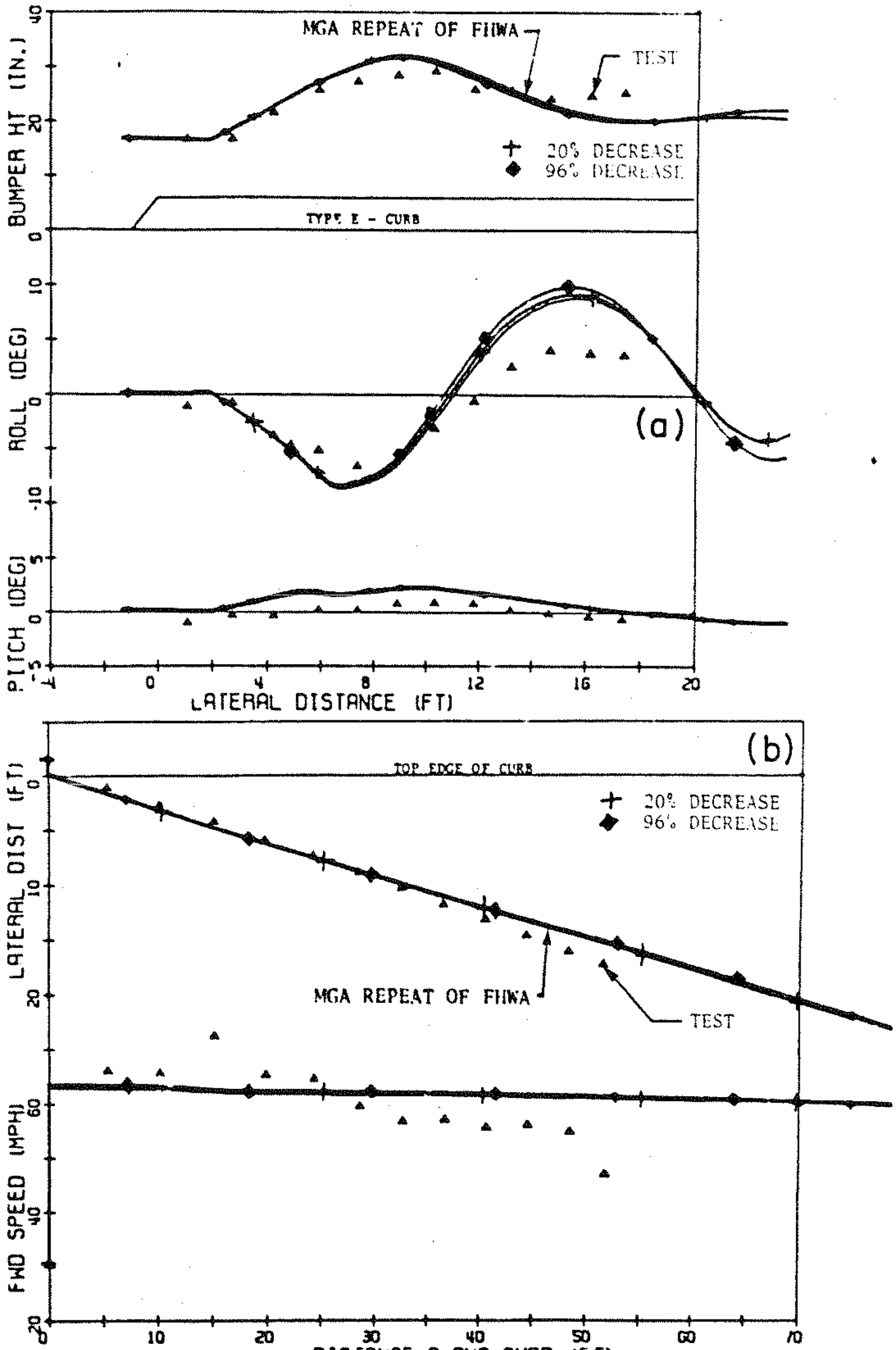


Figure 89 STEERING SYSTEM FRICTION CURB TYPE E, TEST N-10 AT 60 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

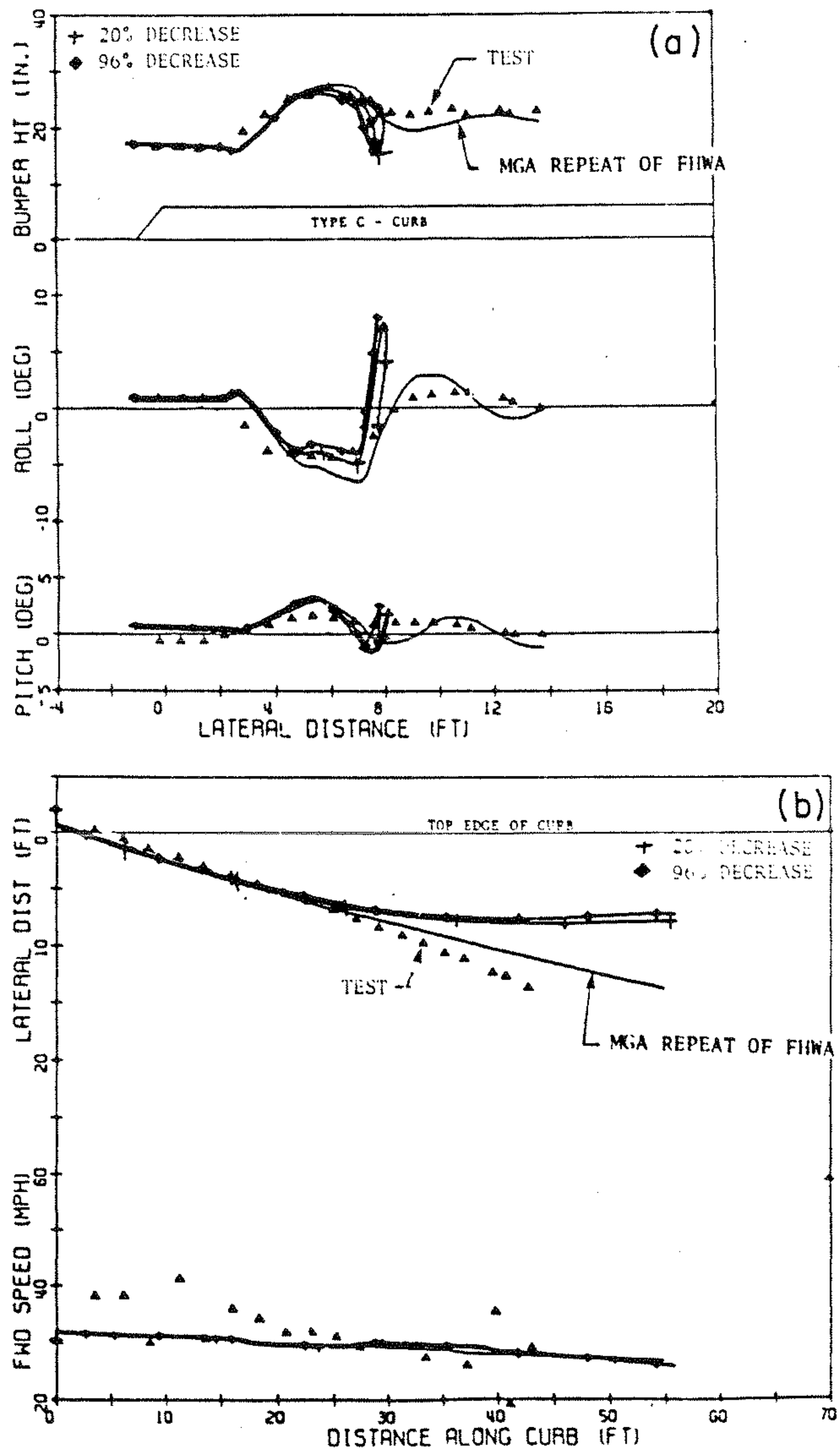


Figure 90 STEERING SYSTEM FRICTION CURB TYPE C, TEST N-15 AT 30 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

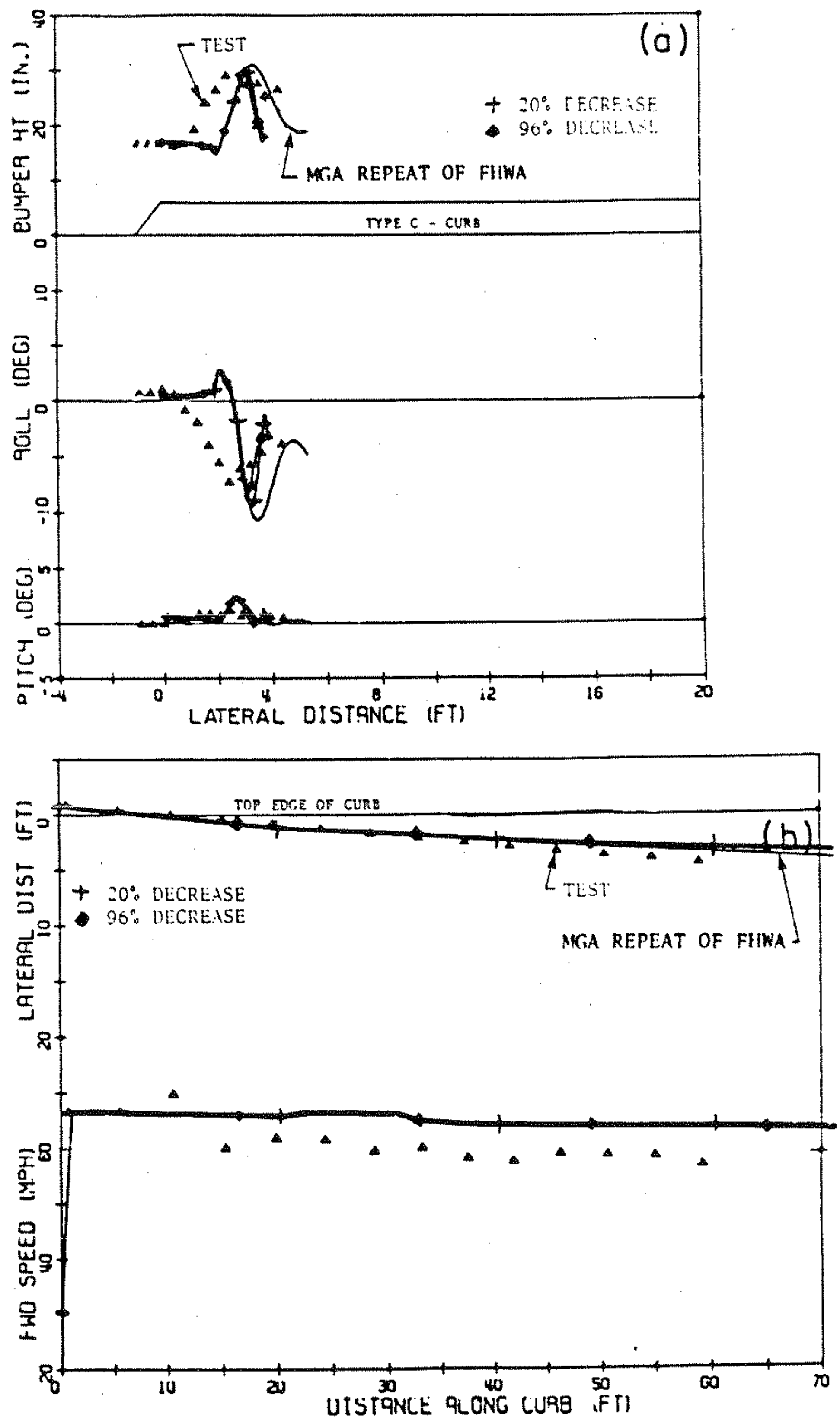


Figure 91 STEERING SYSTEM FRICTION CURB TYPE C, TEST N-17 AT 60 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

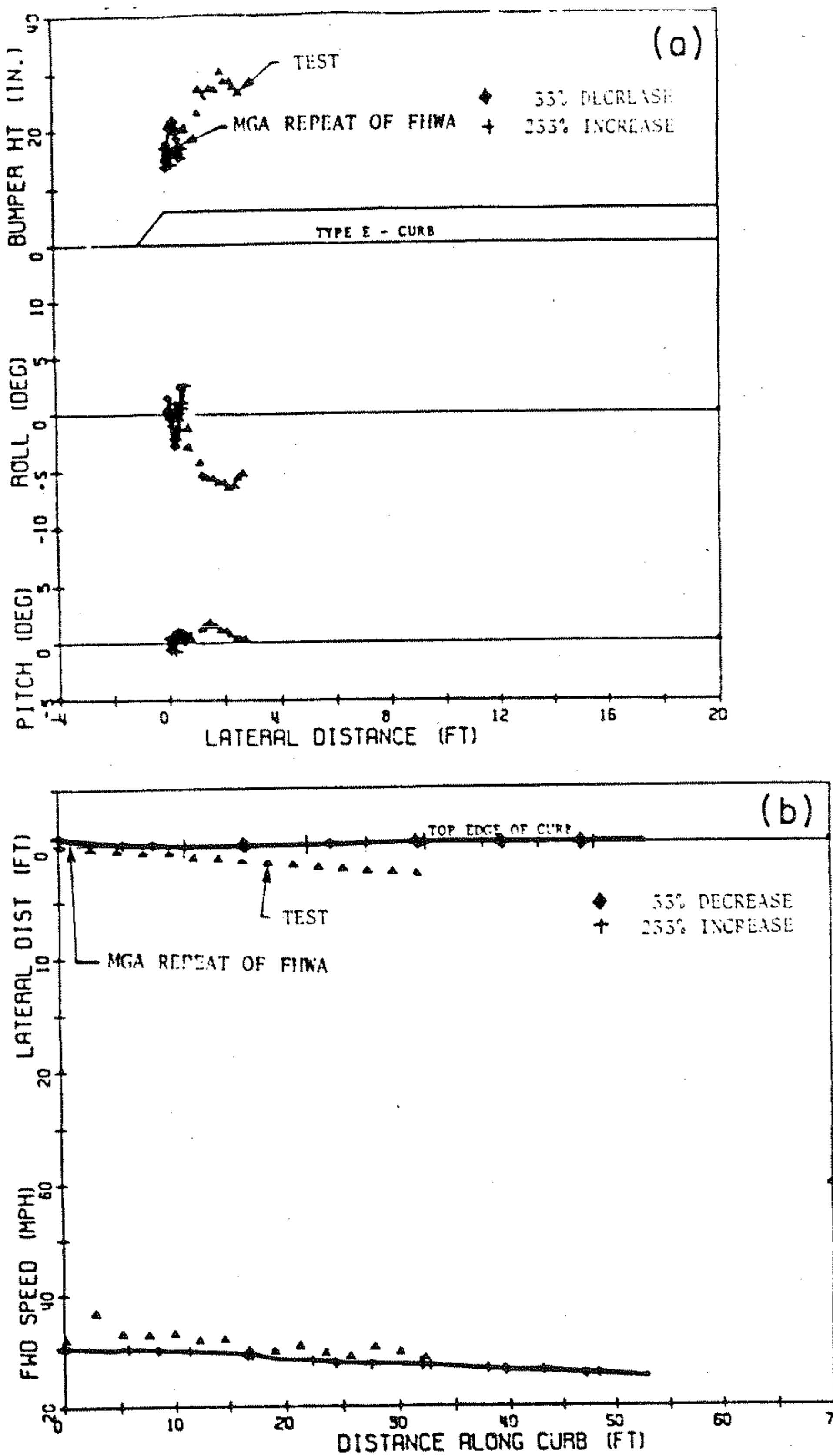


Figure 92 STEERING SYSTEM INERTIA CURB TYPE E, TEST N-2 AT 30 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

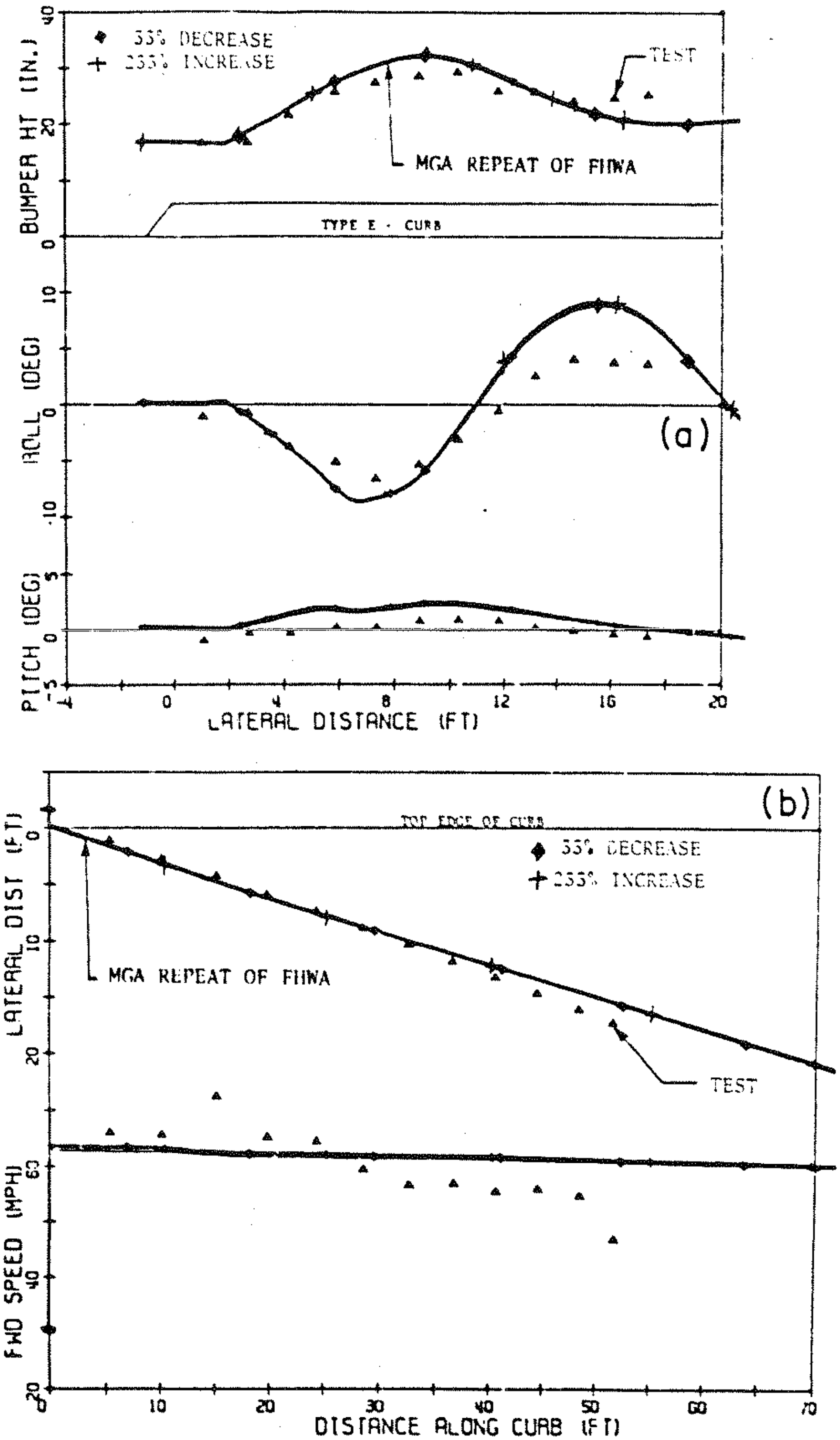


Figure 93 STEERING SYSTEM INERTIA CURB TYPE E, TEST N-10 AT 60 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

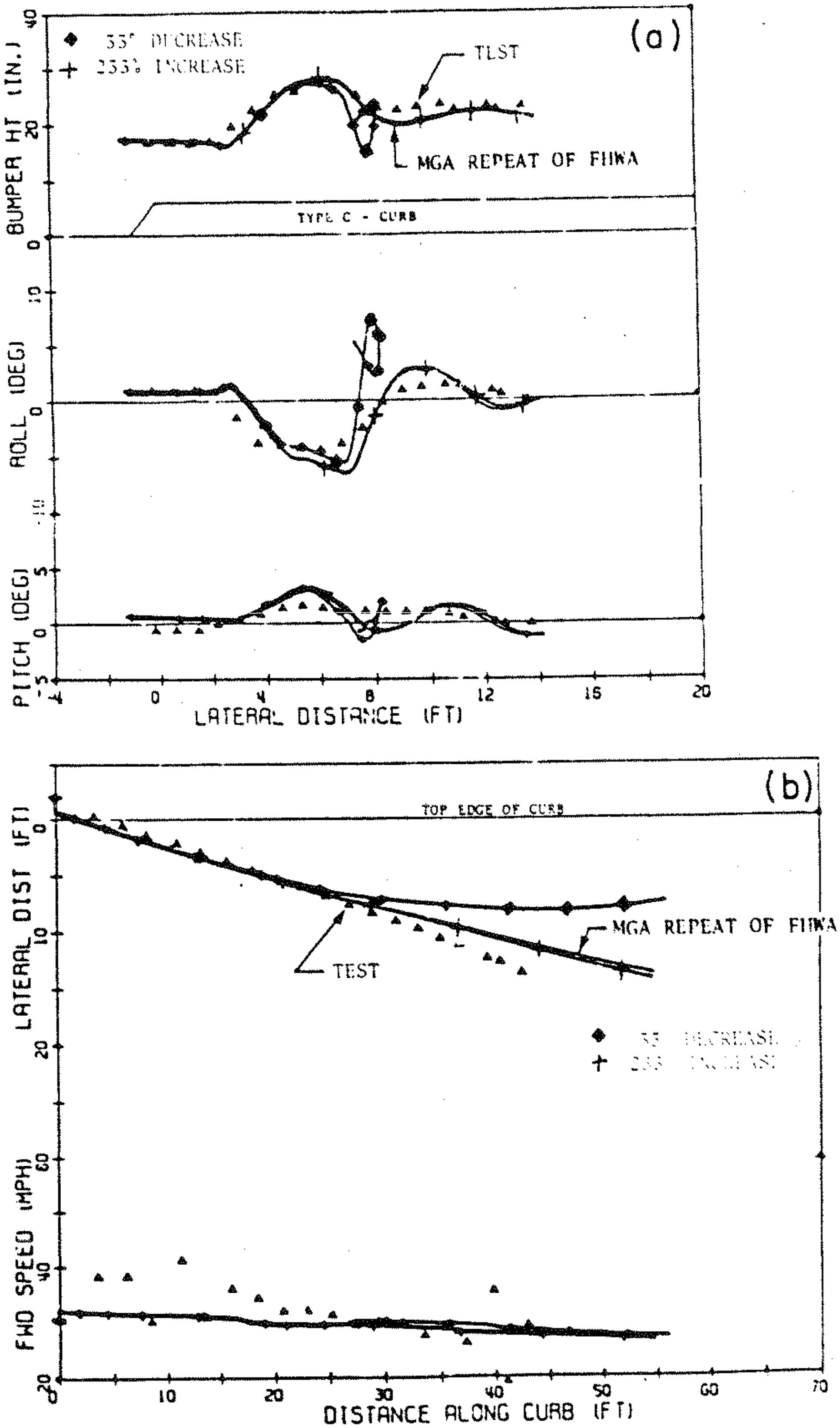


Figure 94 STEERING SYSTEM INERTIA CURB TYPE C, TEST N-15 AT 30 MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

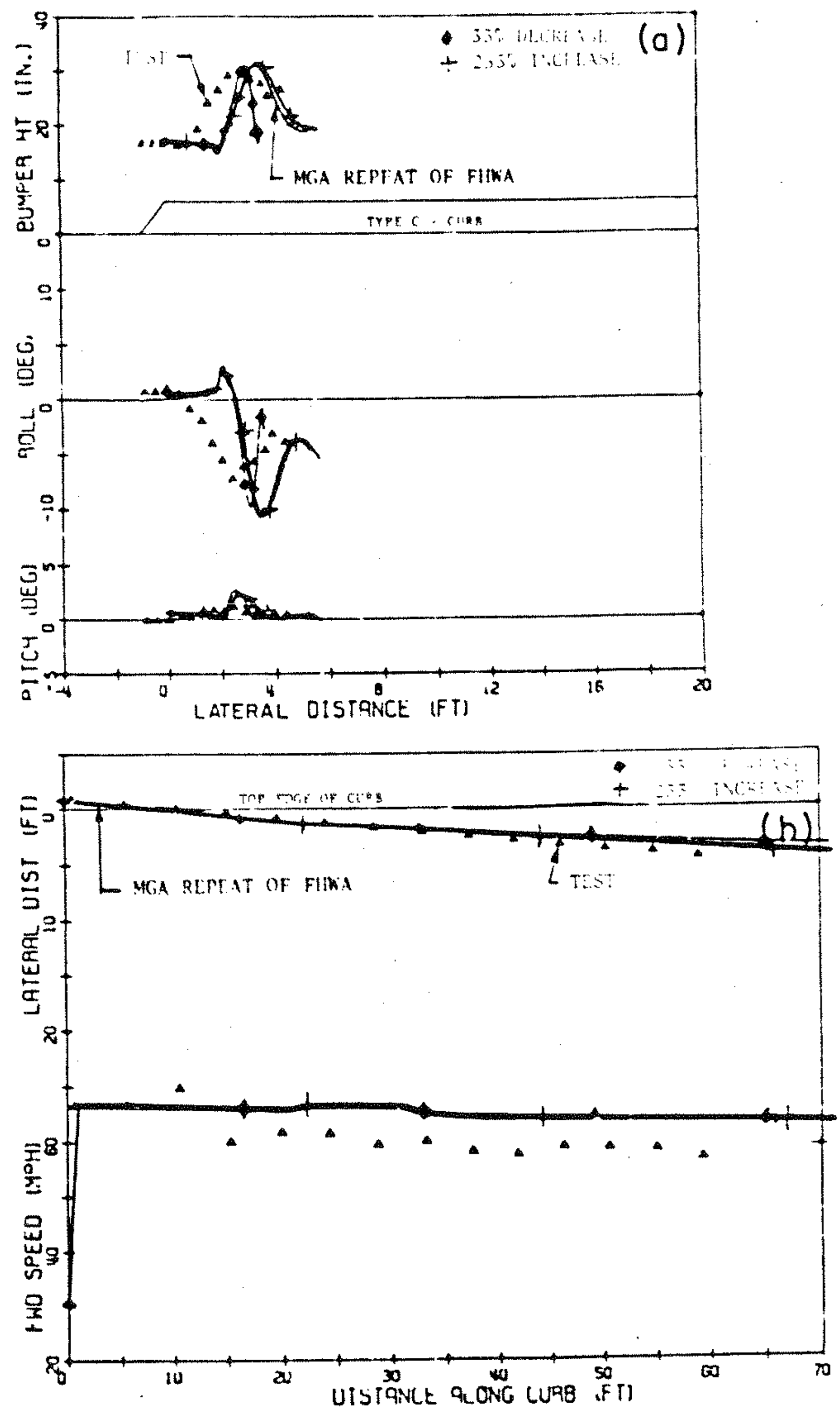


Figure 95 STEEP'NG SYSTEM INERTIA CURB TYPE C, TEST N-17 AT 60 MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

APPENDIX D

MGA "BEST" DATA SET RUNS

Figures 96 through 113 show the HVOSM results of the MGA runs using the best data set in simulating NCHRP 150 runs N-2 through N-19. The results are plotted against the corresponding NCHRP 150 results. Each figure is a comparison of the full-scale NCHRP 150 results (denoted by the individual triangles and labeled "TEST"), the NCHRP 150 simulation results (denoted by the dashed line and labeled "NCHRP 150"), and the results of the MGA best data runs (denoted by the line with the diamond symbols and labeled "MGA BEST DATA"). Each figure is composed of two parts. Part (a) plots vehicle pitch angle, roll angle, and bumper height 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.

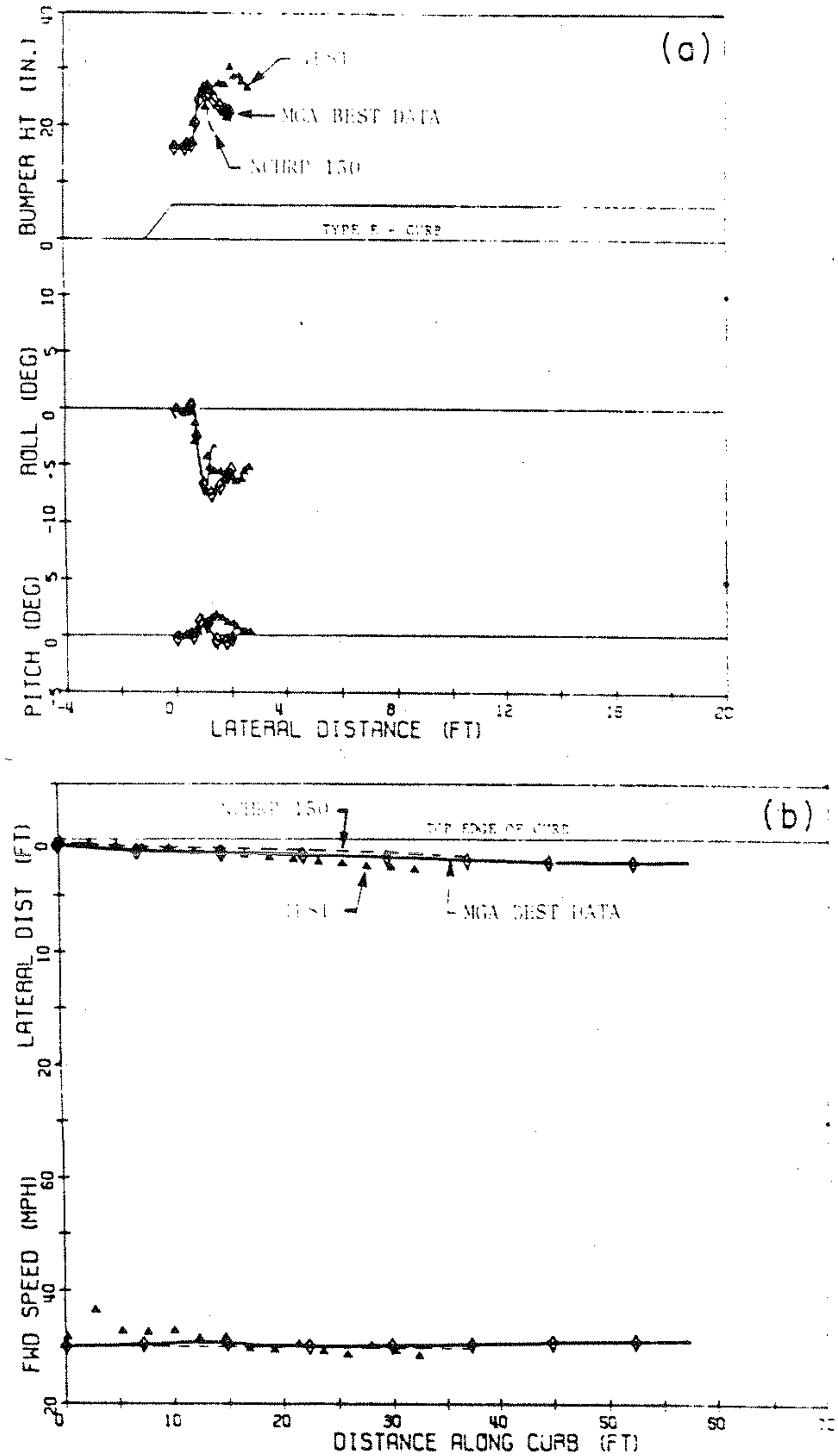


Figure 96 CURB TYPE E, TEST N-2 AT 30-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

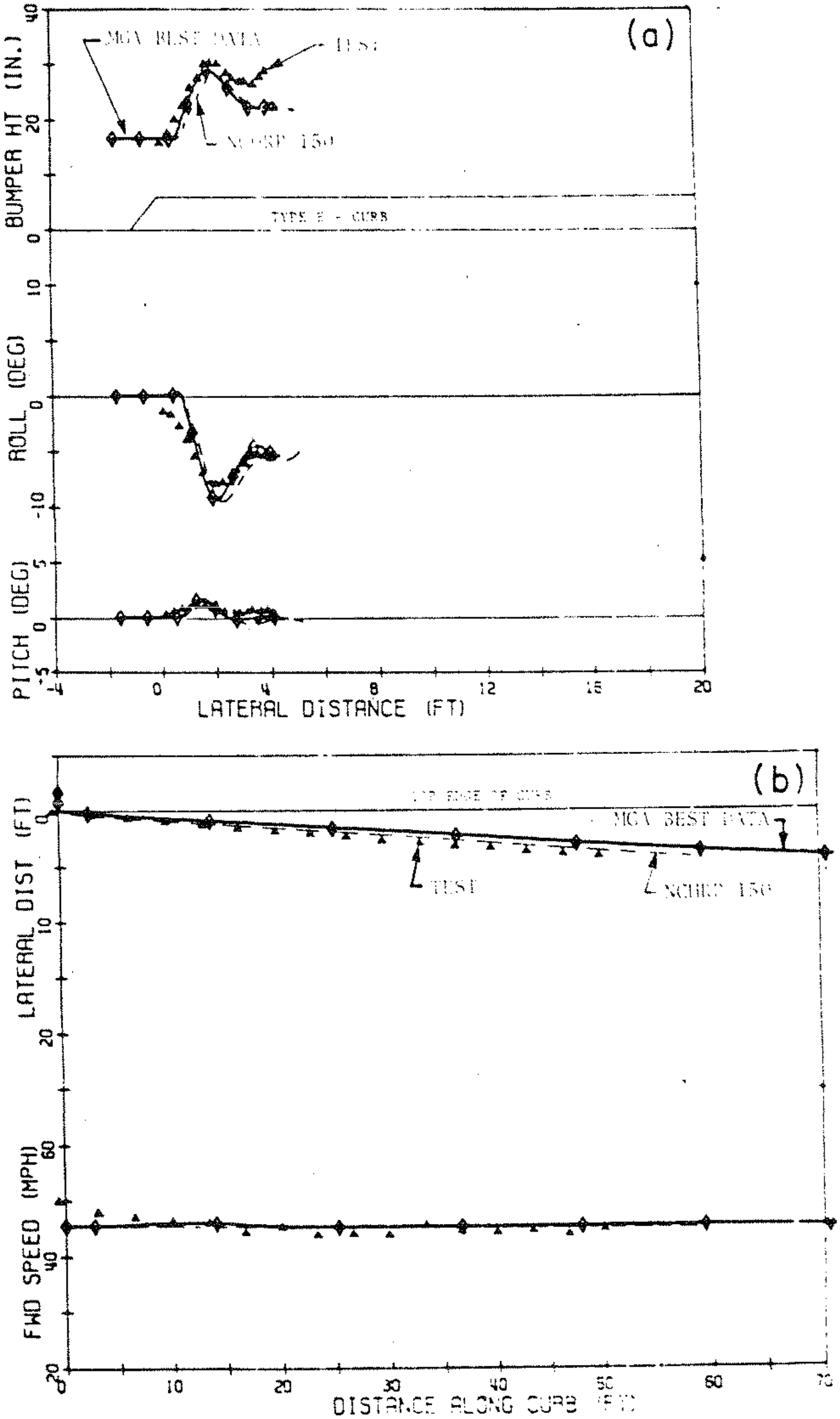


Figure 97 CURB TYPE E, TEST N-3 AT 45-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

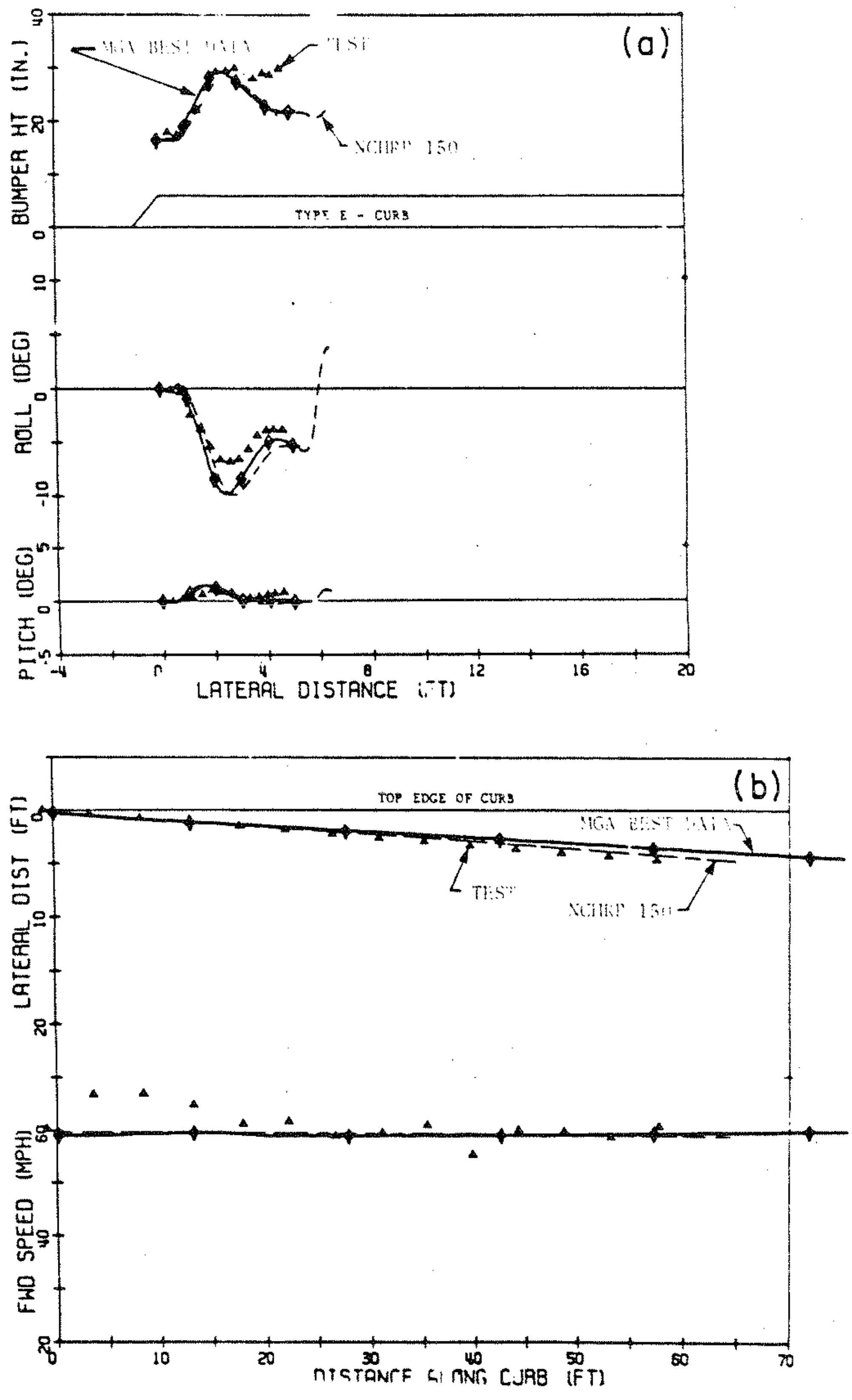


Figure 98 CURB TYPE E, TEST N-4 AT 60-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

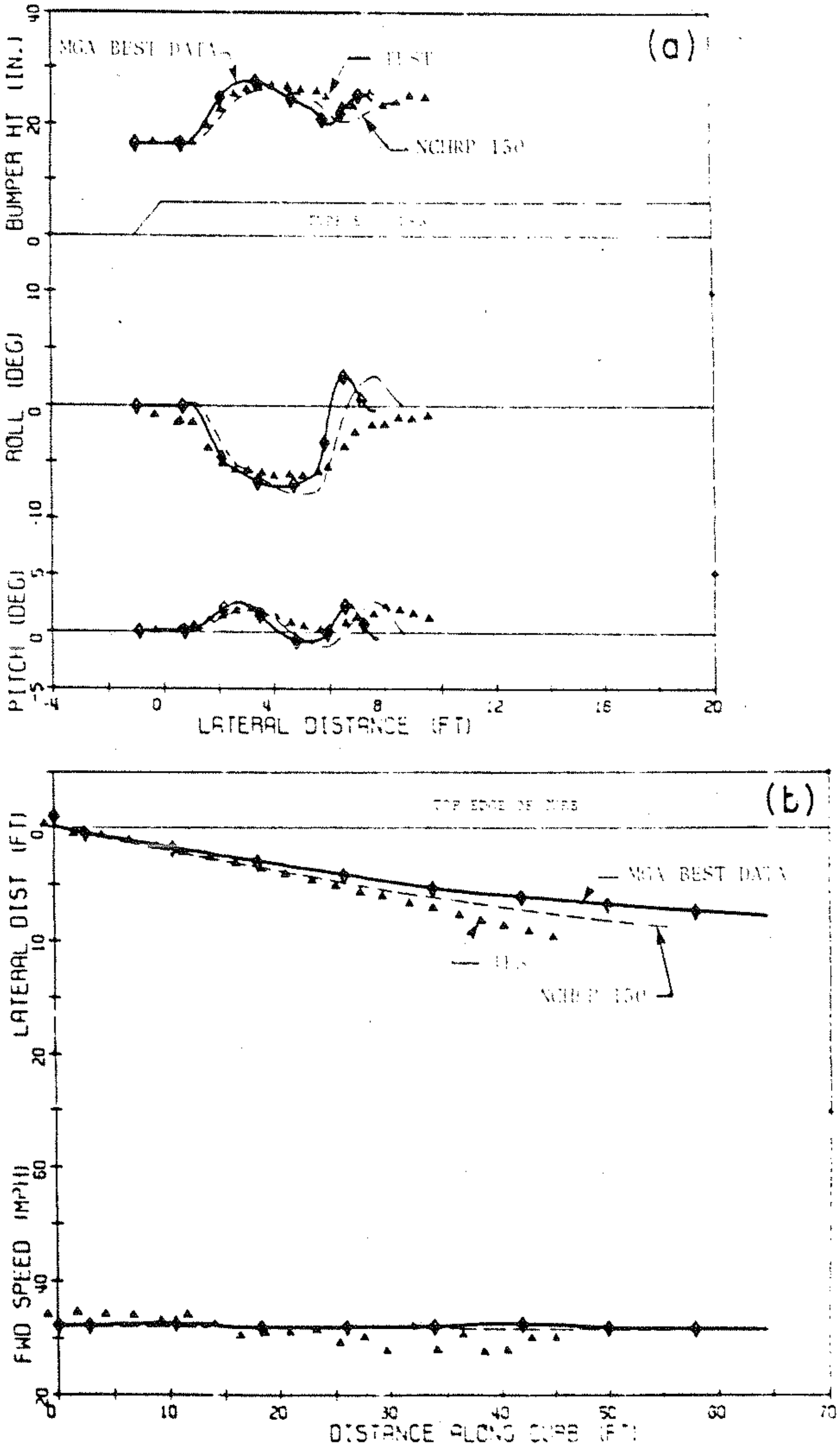


Figure 99 CURB TYPE E, TEST N-5 AT 30-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

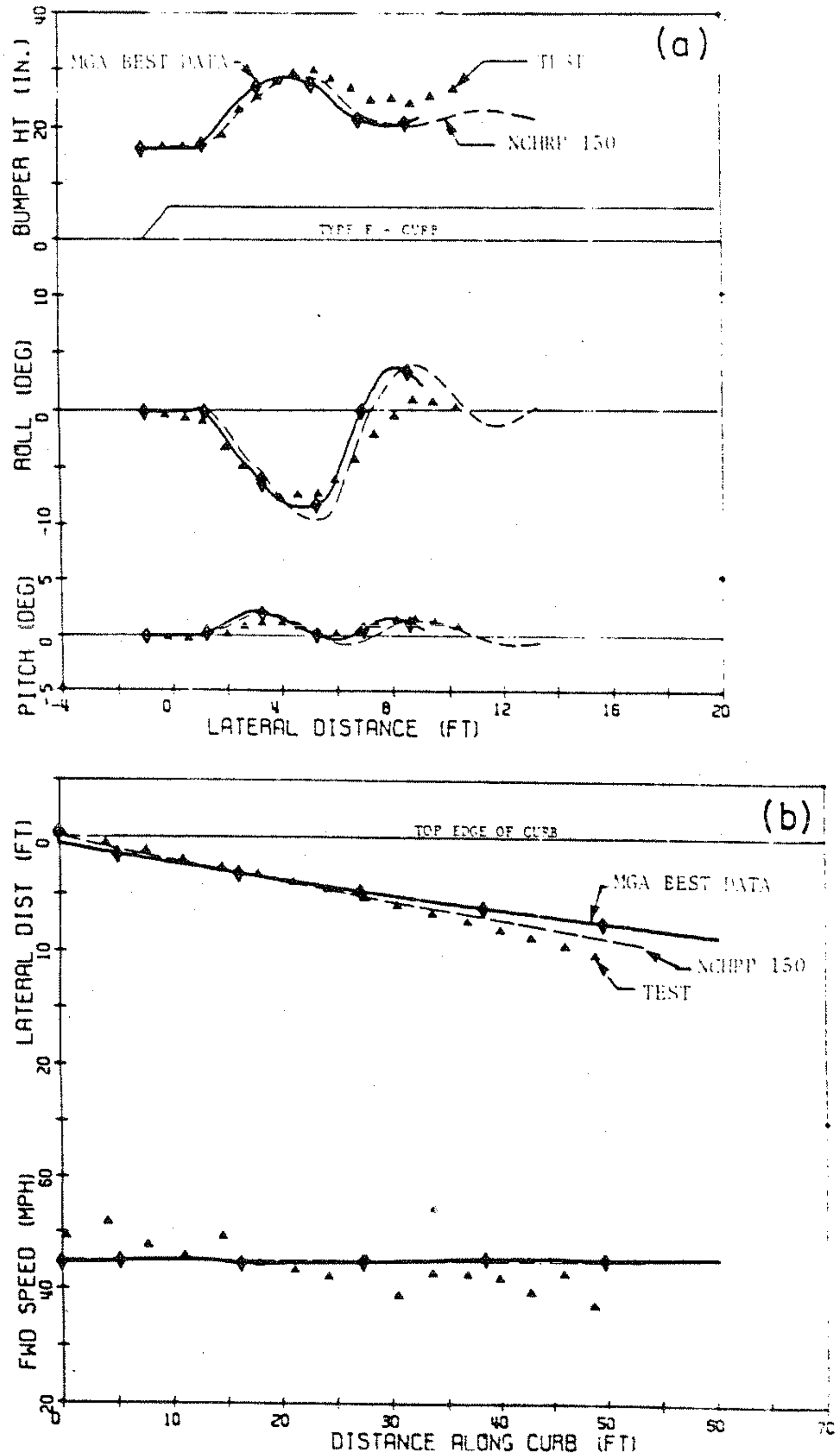


Figure 100 CURB TYPE E, TEST N-6 AT 45-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

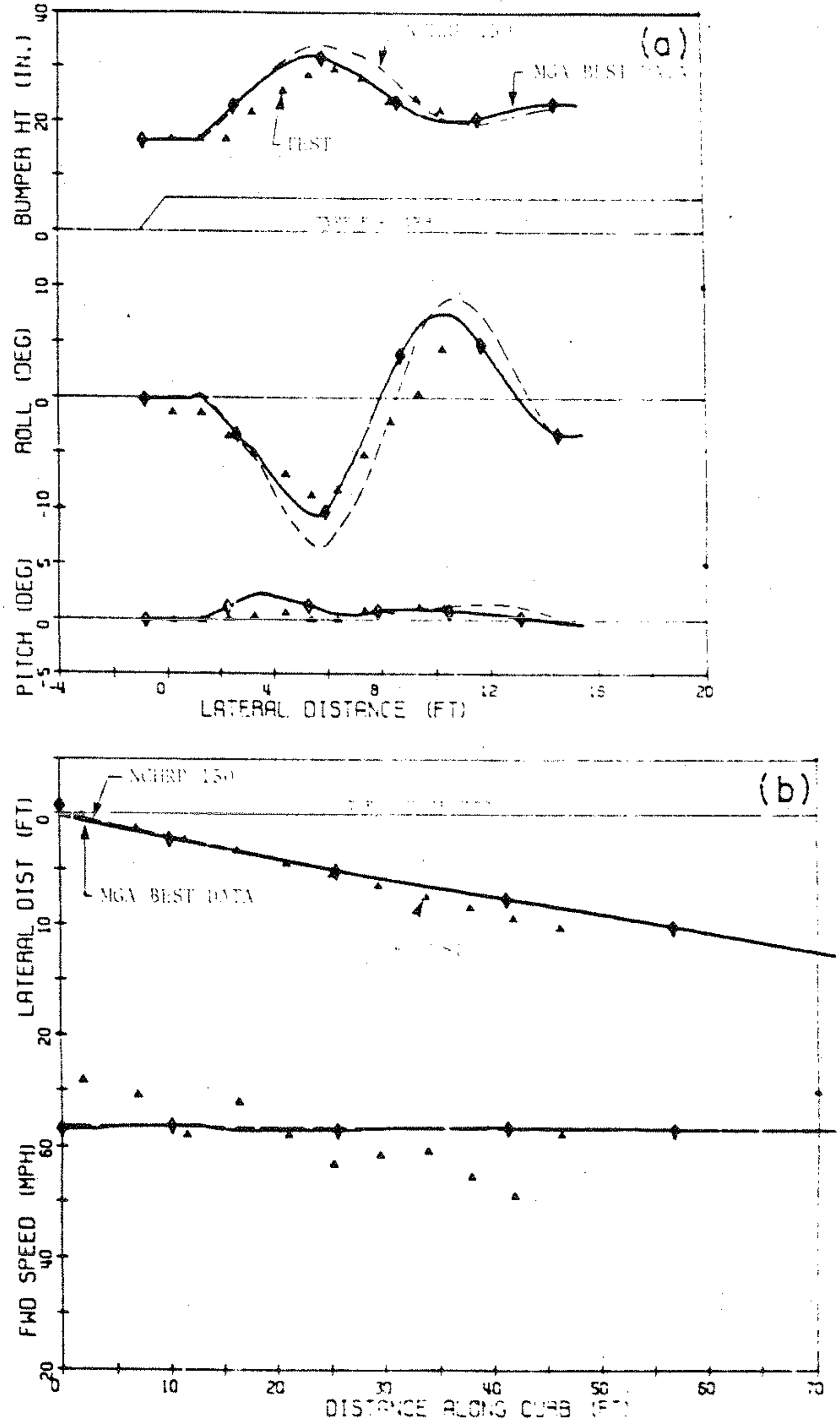


Figure 101 CURB TYPE E, TEST N-7 AT 60-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

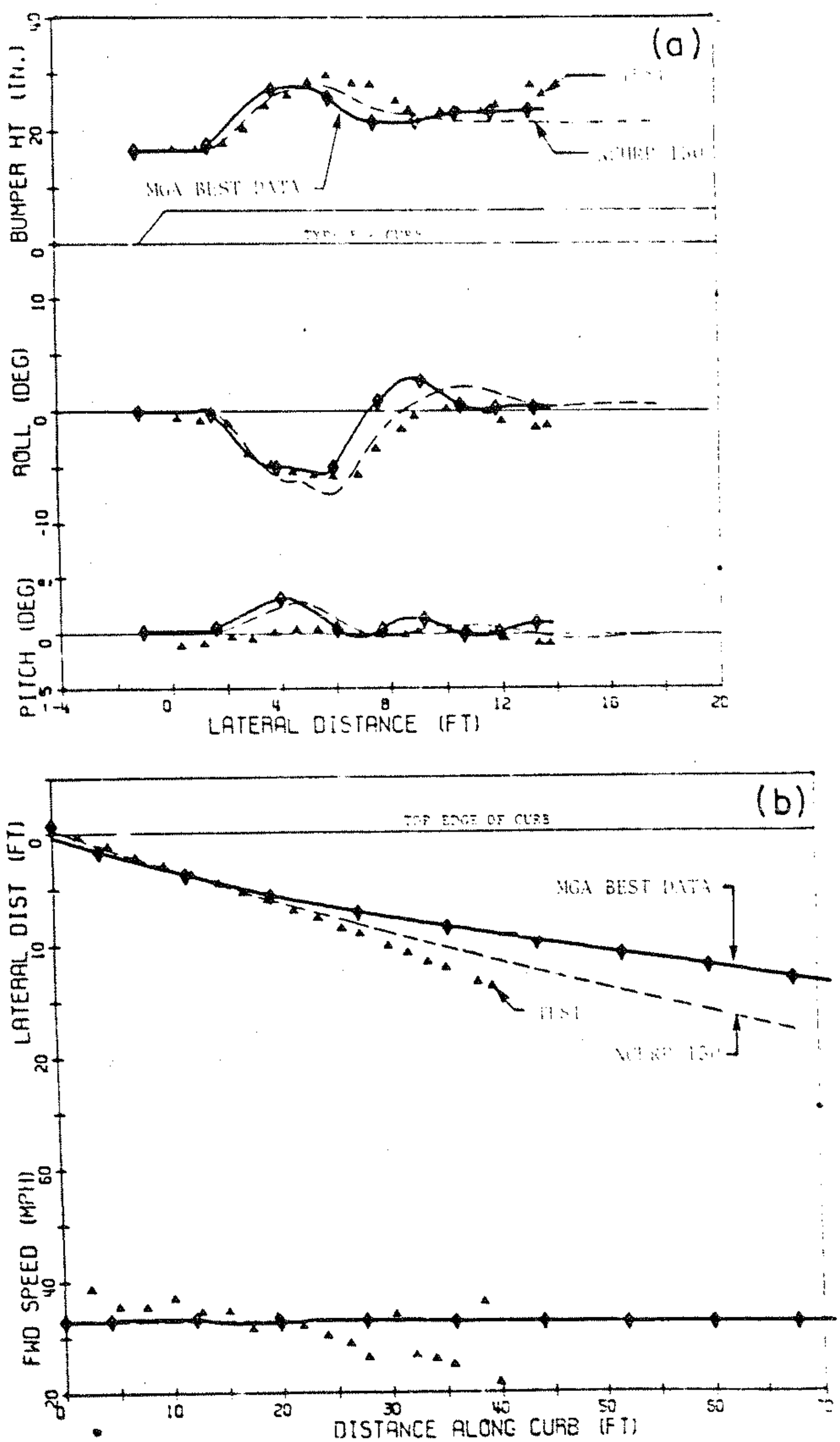


Figure 102 CURB TYPE E, TEST N-8 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

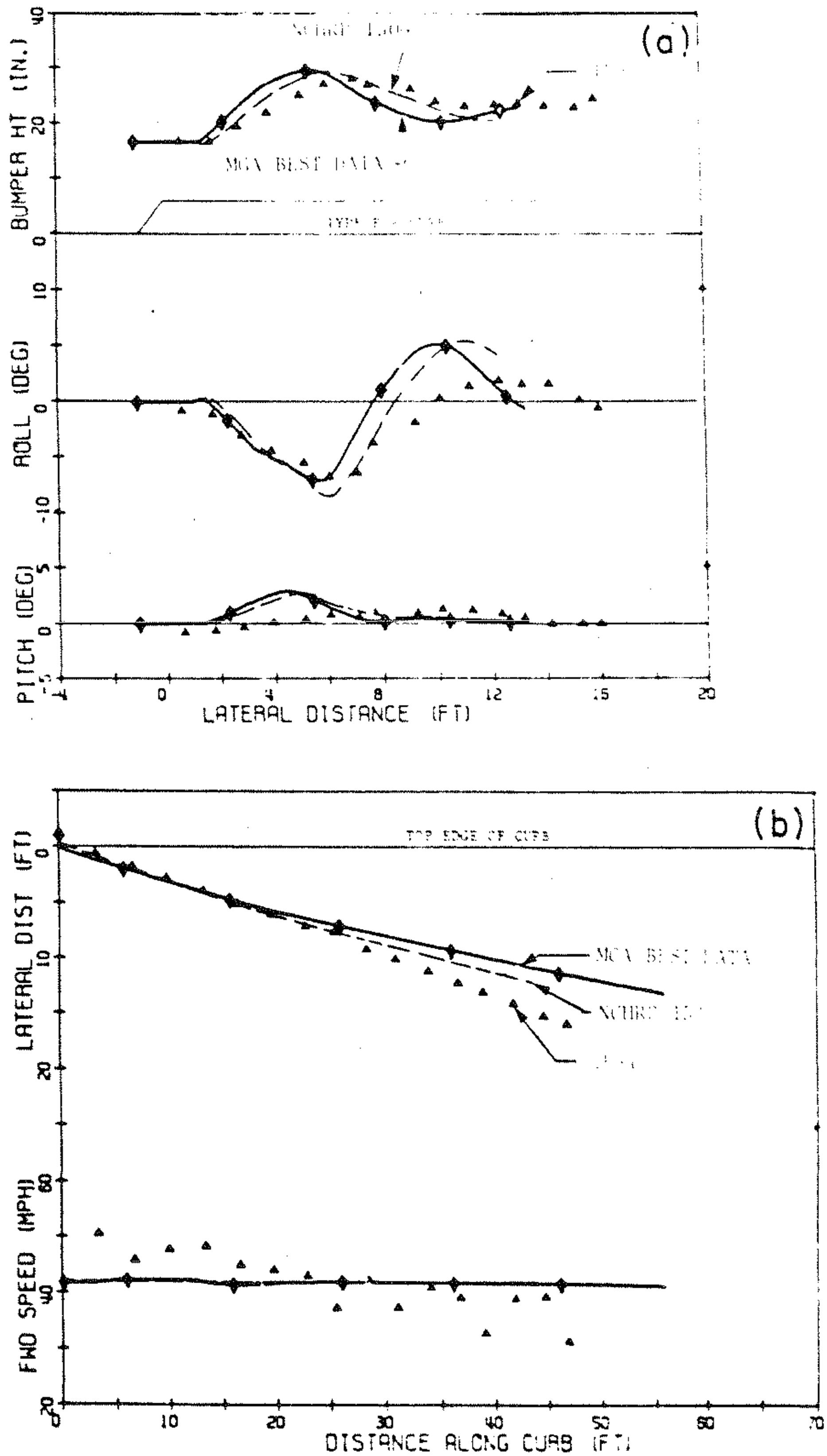


Figure 103 CURB TYPE E, TEST N-9 AT 45-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

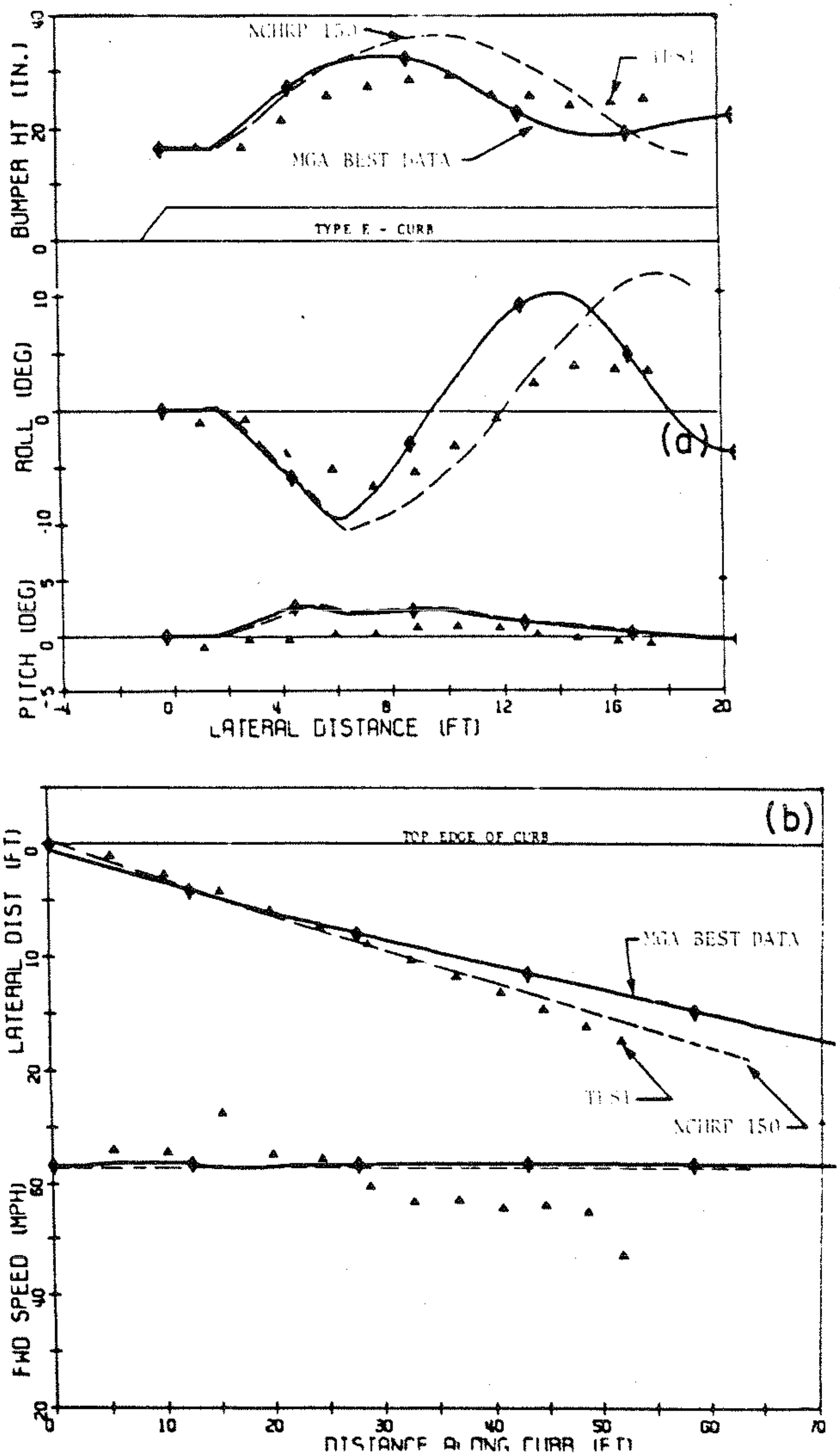


Figure 104 CURB TYPE E, TEST N-10 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

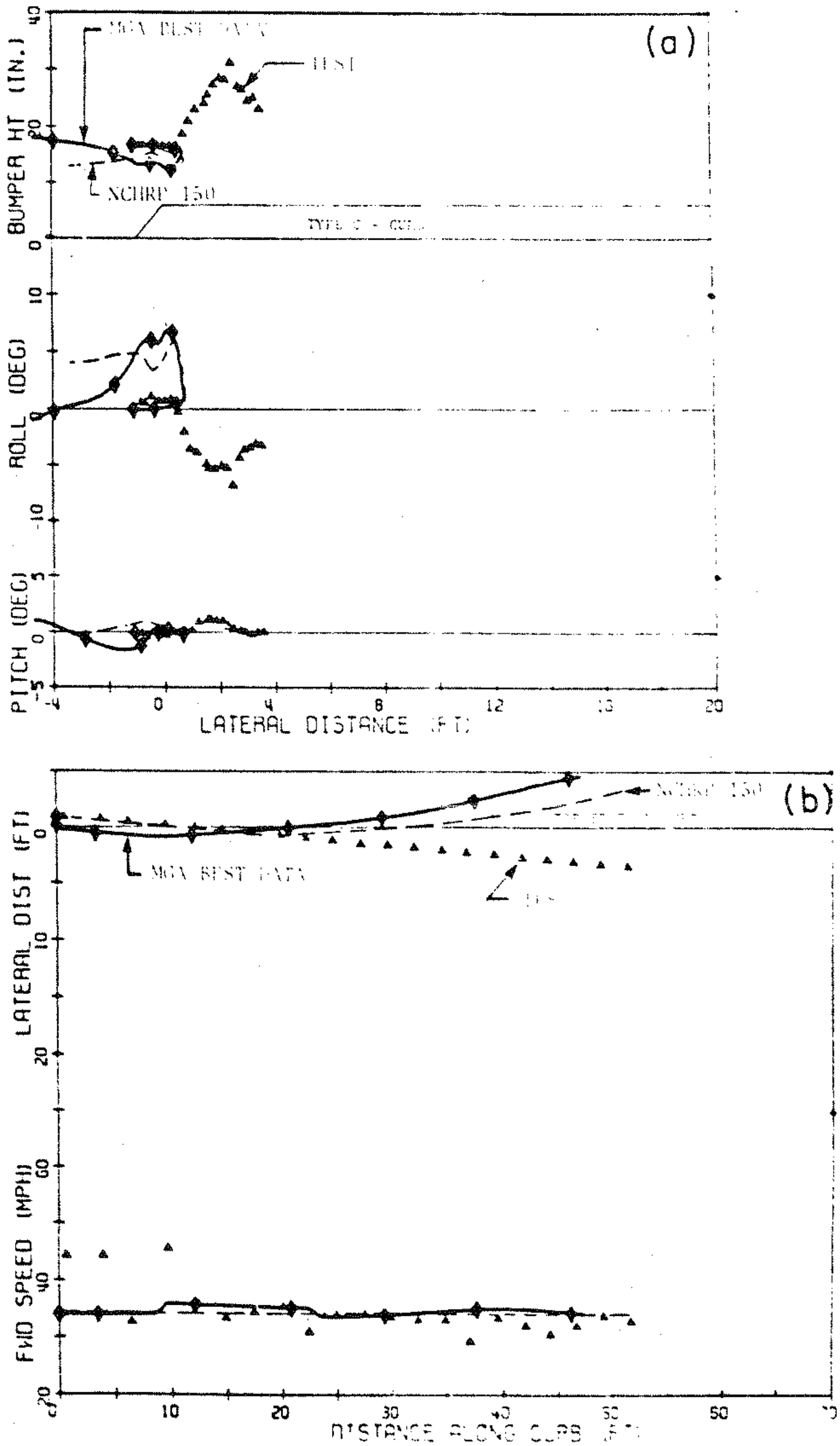


Figure 105 CURB TYPE C, TEST N-11 AT 30-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

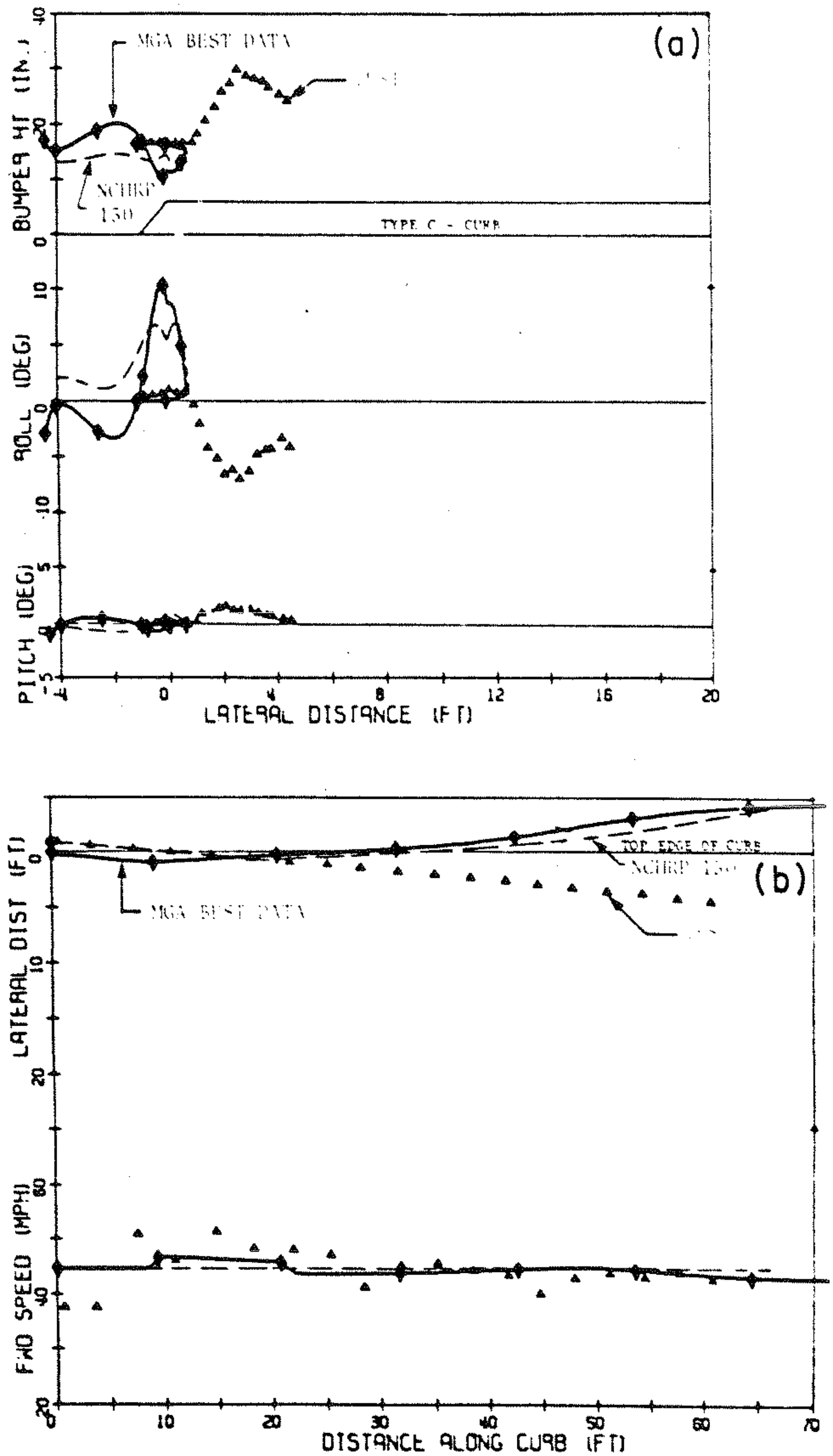


Figure 106 CURB TYPE C, TEST N-12 AT 45-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

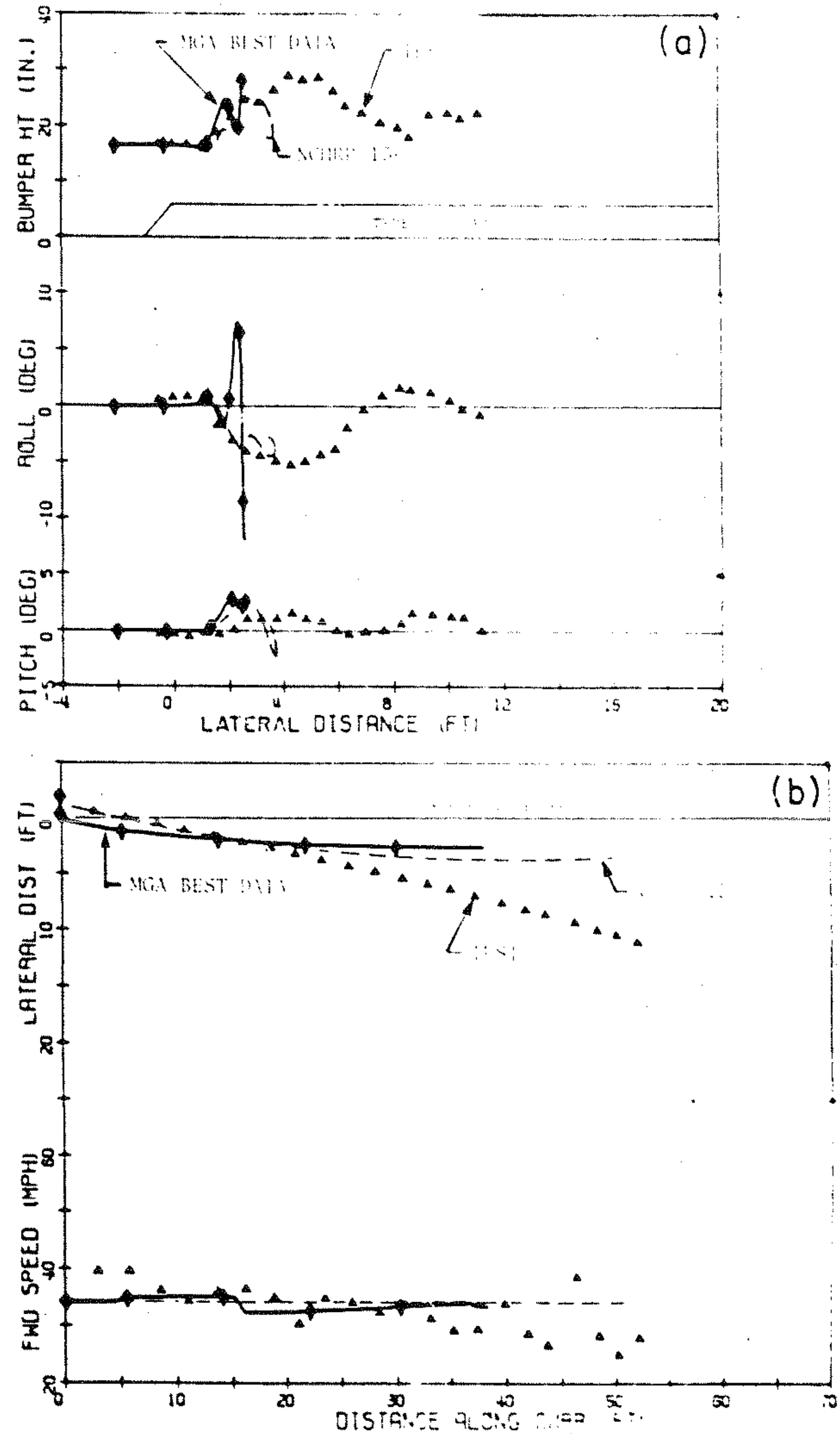


Figure 107 CURB TYPE C, TEST N-13 AT 30-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

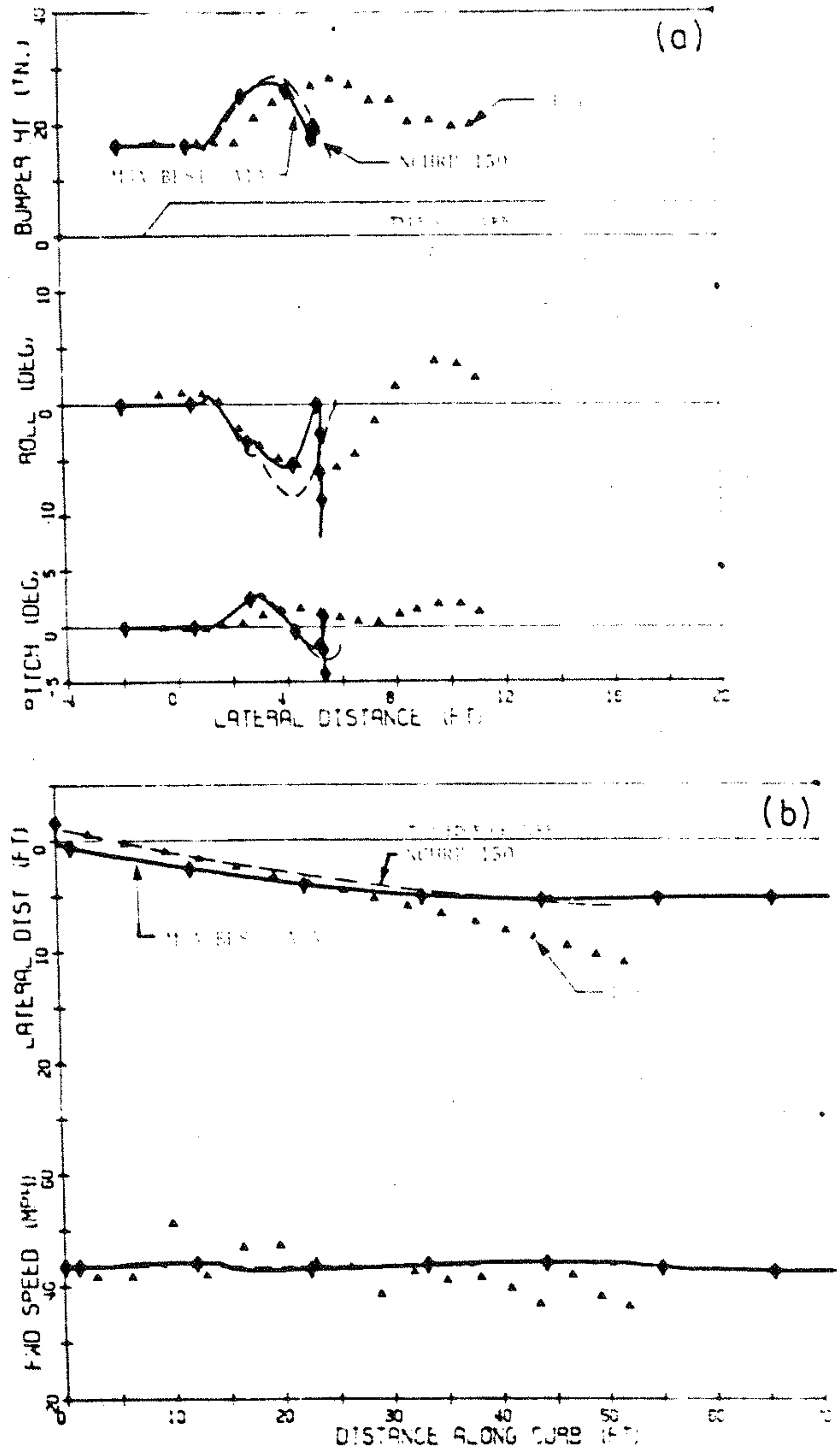


Figure 108 CURB TYPE C, TEST N-14 AT 45-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

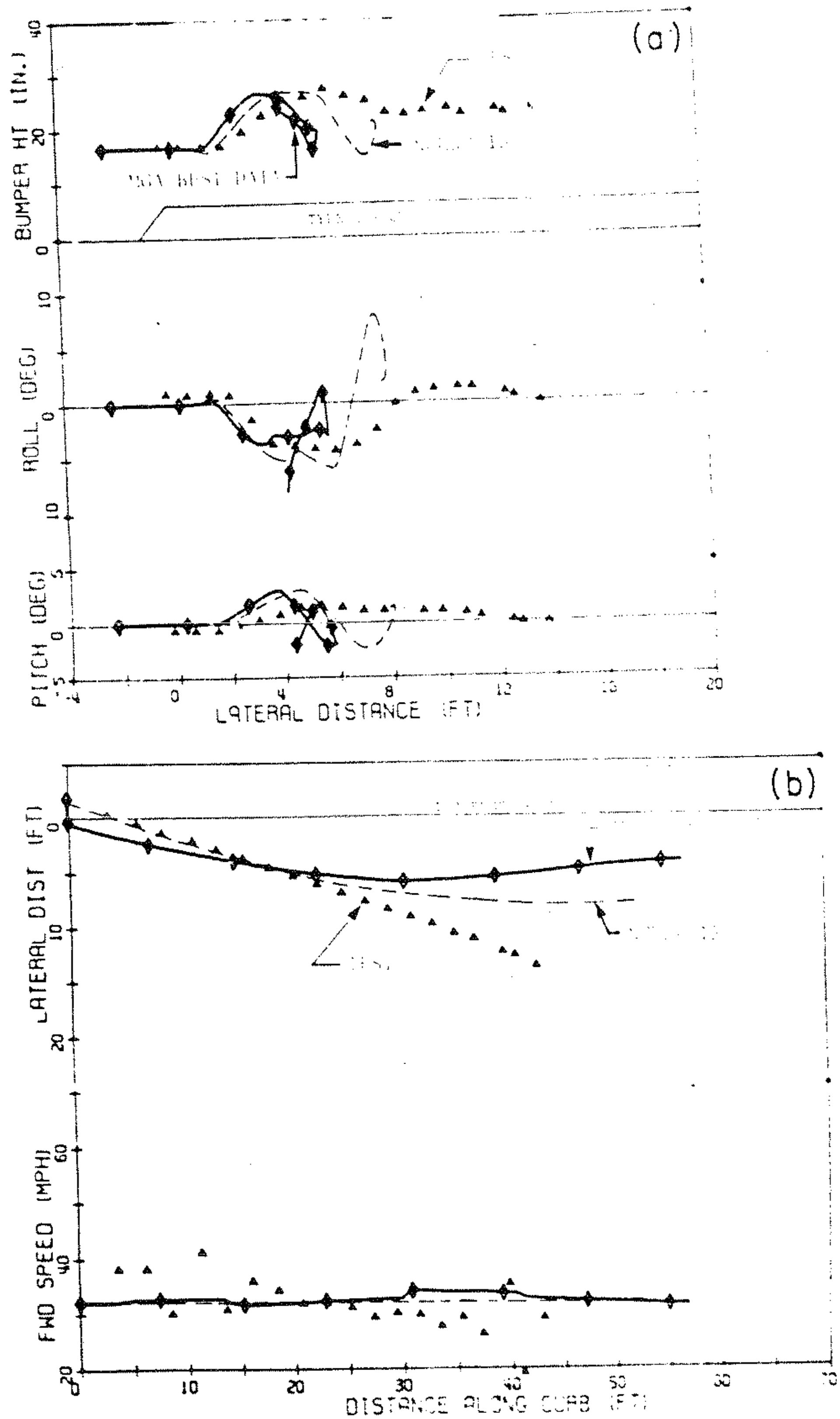


Figure 109 CURB TYPE C, TEST N-15 AT 30-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

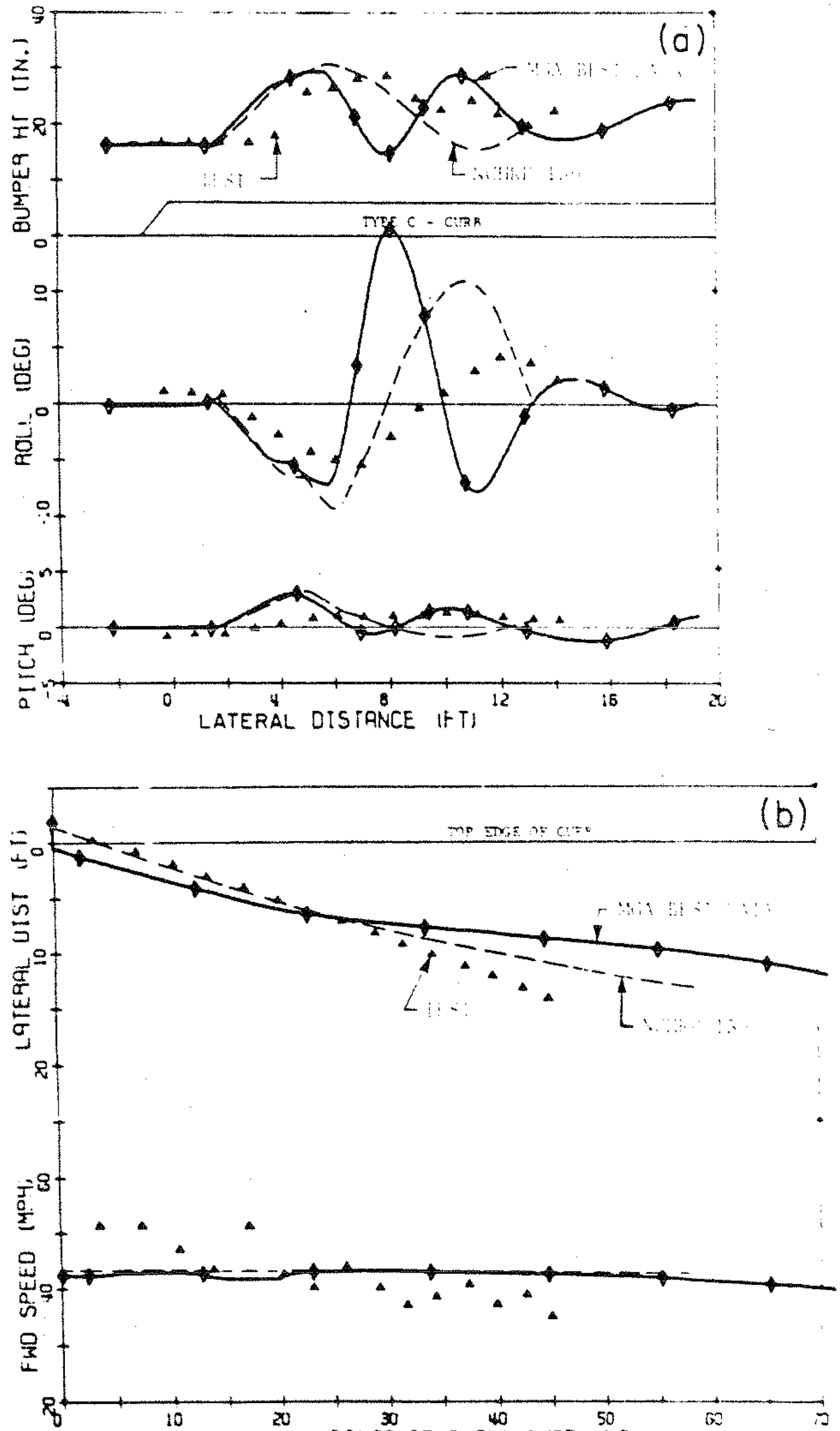


Figure 110 CURB TYPE C, TEST N-16 AT 45-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

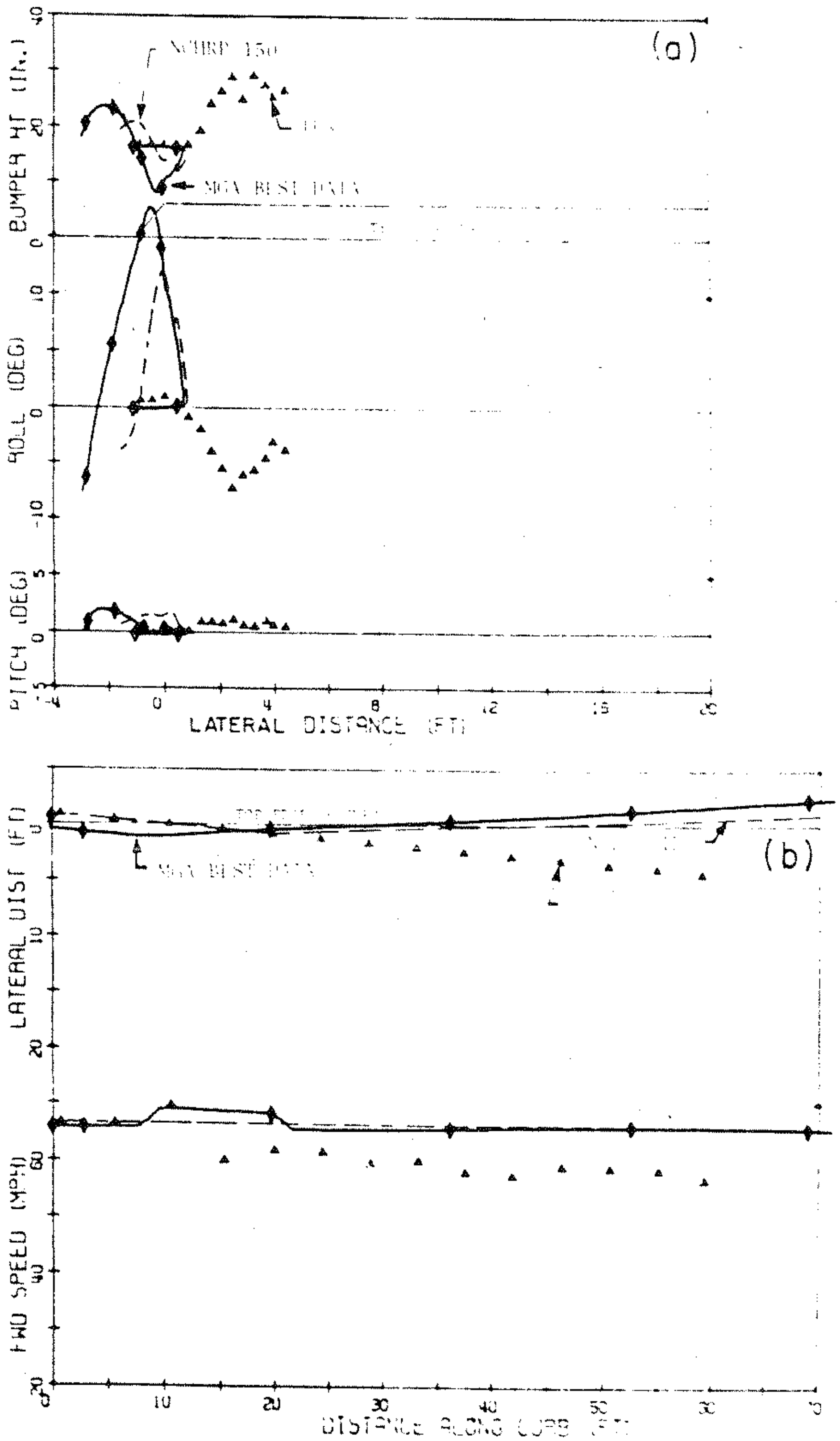


Figure 111 CURB TYPE C, TEST N-17 AT 60-MPH AND 5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

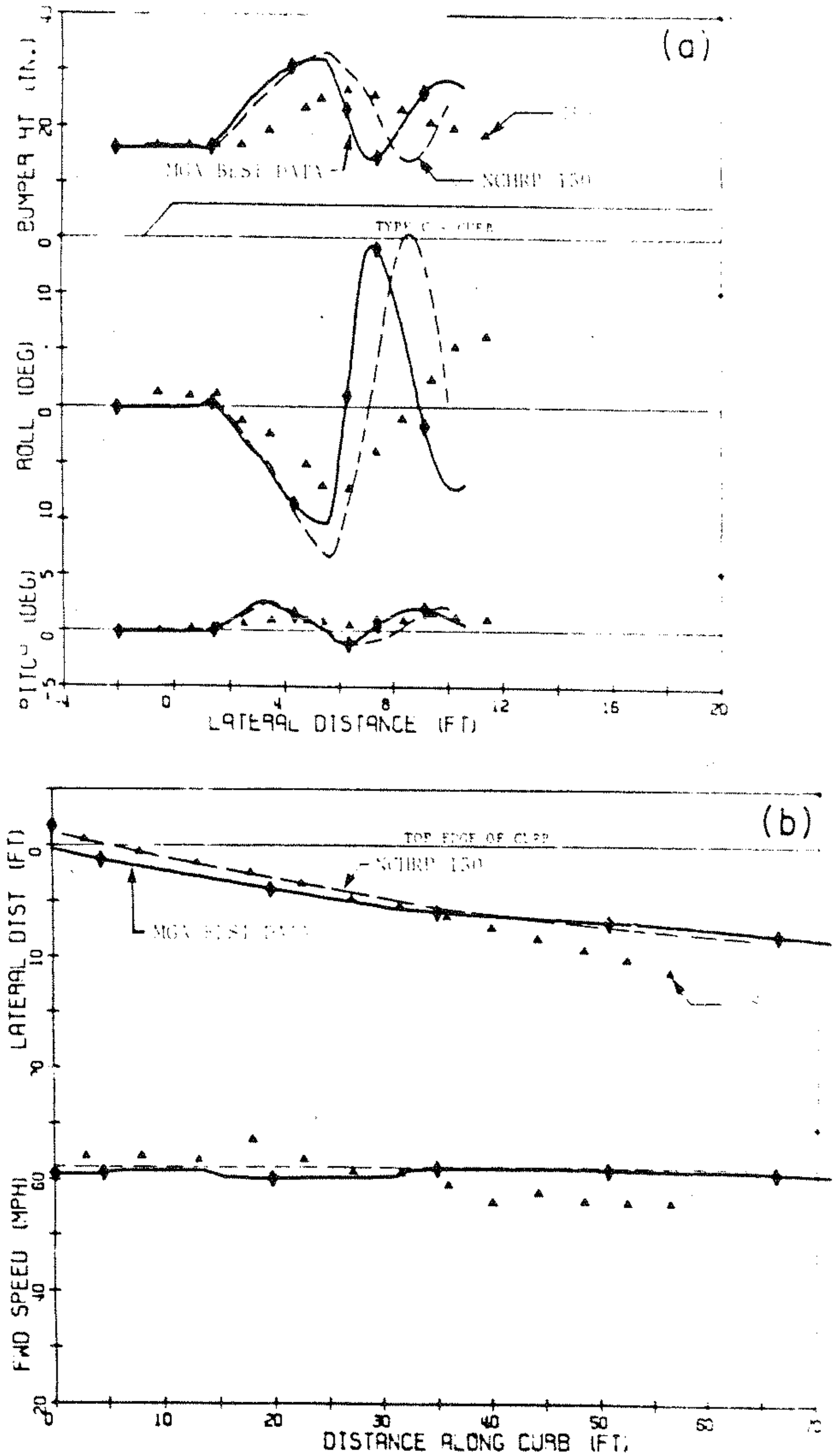


Figure 112 CURB TYPE C, TEST N-18 AT 60-MPH AND 12.5-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

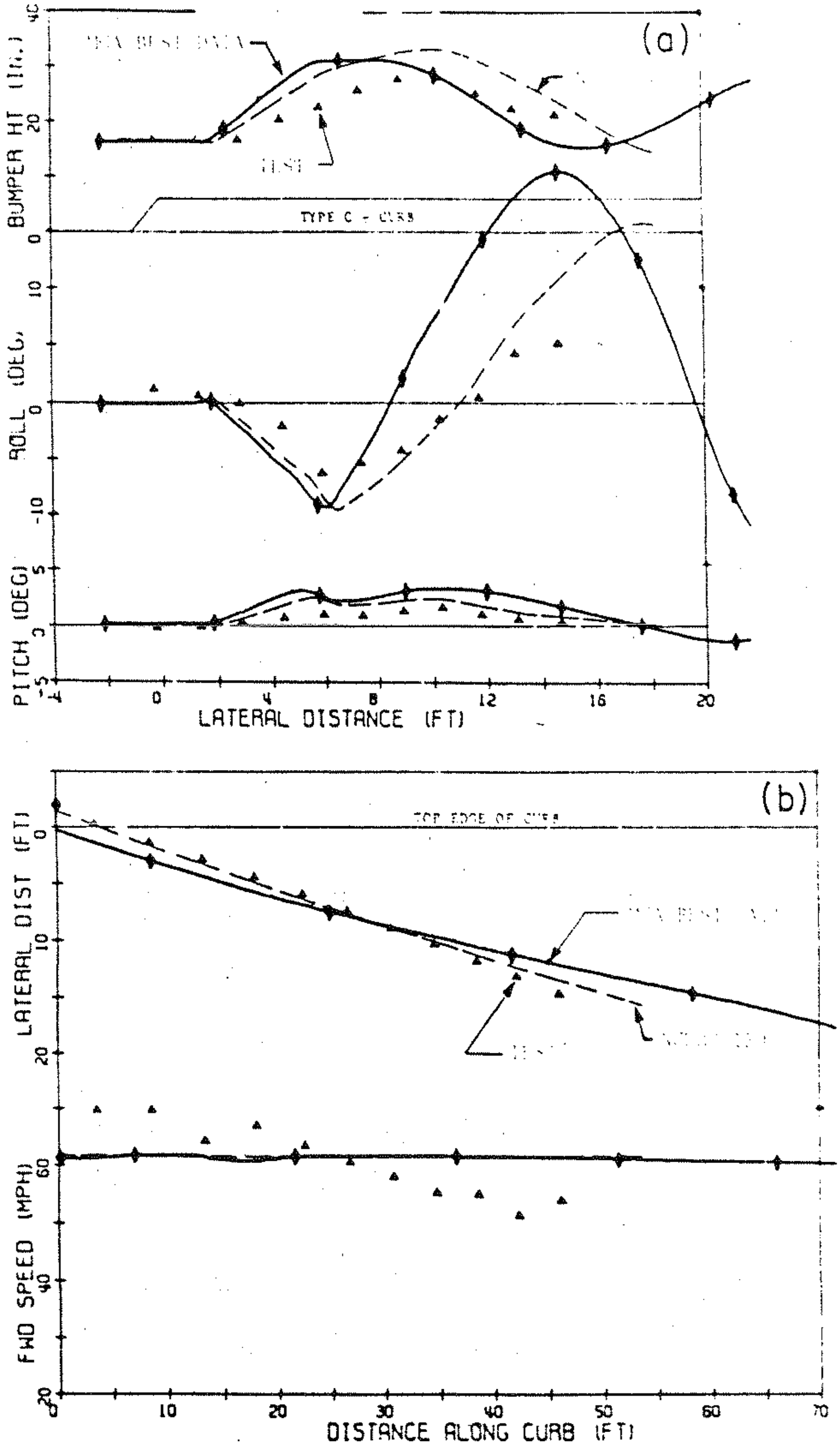


Figure 113 CURB TYPE C, TEST N-19 AT 60-MPH AND 20-DEG IMPACT: (A) VEHICLE ROLL, PITCH, AND BUMPER HEIGHT; (B) VEHICLE SPEED AND PATH

1 in = 25.4 mm
1 ft = 0.305 m
1 mph = 1.609 km/h

GLOSSARY

DESCRIPTION OF INPUT VARIABLES

Variable	Description	Units
Inertial & Dimensional Data:		
M_s	Sprung mass	$lb\text{-}s^2/in$
M_{uf}	Total front unsprung mass	$lb\text{-}s^2/in$
M_{ur}	Total rear unsprung mass	$lb\text{-}s^2/in$
I_x	Mass moment of inertia of the sprung mass about the vehicle X-axis	$lb\text{-}s^2\text{-}in$
I_y	Mass moment of inertia of the sprung mass about the vehicle Y-axis	$lb\text{-}s^2\text{-}in$
I_z	Mass moment of inertia of the sprung mass about the vehicle Z-axis	$lb\text{-}s^2\text{-}in$
I_{xz}	Mass product of inertia of the sprung mass in the vehicle X-Z plane	$lb\text{-}s^2\text{-}in$
I_r	Mass moment of inertia of the solid axle rear unsprung mass about a line parallel to the vehicle X-axis and through the rear unsprung mass center of gravity	$lb\text{-}s^2\text{-}in$
a	Horizontal distance from spurng mass c.g. to centerline of front wheels	in
b	Horizontal distance from sprung mass c.g. to centerline of rear wheels	in
T_f	Front wheel track	in
T_r	Rear wheel track	in
ρ	Vertical distance between rear axle c.g. and rear axle roll center, positive for roll center above c.g.	in
T_s	Distance between rear spring moments for solid rear axle	in
Suspension Rate Data:		
K_f	Linear front suspension load delfection rate	lb/in
K_{fc}	Linear coefficient of the front suspension compression (jounce) bumper term	lb/in
K'_{fc}	Cubic coefficient of the front suspension compression (jounce) bumper term	lb/in^3
K_{fe}	Linear coefficient of the front suspension extension (rebound) bumper term	lb/in
K'_{fe}	Cubic coefficient of the front suspension extension (rebound) bumper term	lb/in^3

Variable	Description	Units
λ_f	Ratio of conserved to total absorbed energy in the front suspension bumpers	
Ω_{fc}	Front suspension deflection at which the compression bumper is contacted (should be negative)	in
Ω_{fe}	Front suspension deflection at which the extension bumper is contacted (should be positive)	in
K_r	Linear rear suspension load deflection rate	lb/in
Krc	Linear coefficient of the rear suspension compression (jounce) bumper term	lb/in
K'rc	Cubic coefficient of the rear suspension compression (jounce) bumper term	lb/in^3
Kre	Linear coefficient of the rear suspension extension (rebound) bumper term	lb/in
K're	Cubic coefficient of the rear suspension extension (rebound) bumper term	lb/in^3
λ_r	Ration of conserved to total absorbed energy in the rear suspension bumpers	
Ωrc	Rear suspension deflection at which the compression bumper is contacted (should be negative)	in
Ω_{re}	Rear suspension deflection at which the extension bumper is contacted (should be positive)	in

Suspension & Steering Data:

Variable	Description	Units
C_f	Front suspension viscous damping coefficient per side	lb-s/in
C'_f	Front suspension coulomb friction per side	lb
ϵ_f	Front suspension friction null band	in/s
C_r	Rear suspension viscous damping coefficient per side	lb-s/in
C'_r	Rear suspension coulomb friction per side	lb
ϵ_r	Rear suspension friction null band	in/s
R_f	Front suspension auxiliary roll stiffness	lb-in/rad
Rr	Rear suspension auxiliary roll stiffness	lb-in/rad
K_{rs}	Rear axle roll-steer coefficient	
I_ψ	Steering system steer moment of inertia about the wheel steering axes	$lb\text{-}s^2\text{-}in$
C'_ψ	Steering system coulomb friction torque, effective at the wheel steering axes	lb-in

GLOSSARY (CONTINUED)

Variable	Description	Units
δ_ψ	Front wheel steer angle at which steering limit stops are engaged	rad
K_ψ	Stiffness of the steering limit stops, effective at the front wheel	lb-in/rad
ϵ_ψ	Friction lag in the steering system	rad/s
PT	Front wheel pneumatic trail	in
Tire Data:		
RWHJE	Final deflection of the force versus deflection characteristic of the radial spring tire model	in
DRWHJ	Increment of deflection of the force versus deflection characteristic of the radial spring tire model	in
K_t	Tire load-deflection rate in the quasi-linear range	lb/in
σ_t	Tire deflection at which the load deflection rate increases	in
λ_t	Multiplier of Kt used to obtain tire stiffness at large deflections	
A_0	Constant for tire side force vs slip angle characteristic	
A_1	Constant for tire side force characteristic due to slip angle	
A_2	Constant for tire side force characteristic due to slip angle	
A_3	Constant for tire side force characteristic due to camber angle	
A_4	Constant for tire side force characteristic due to camber angle	
Ω_t	Multipler of A2 at which tire side force characteristic variation with load is abandoned	
μ_m	Friction coefficients of surface on which tire measurements were taken	
R_w	Undeflected tire radius	in

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