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HVOSM CURB IMPACT STUDIES

Final Report, Task 2, Subcontract Work Order No. 1,
Contract No. DOT-FH-11-9575,
Effectiveness of Geometric Design Criteria
for Rural Highways

Prepared For

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SUMMARY

The Highway-Vehicle-Object Simulation Model (HVOSM) computer program was applied to predict vehicle responses in curb impacts. The correlation with results of full-scale experiments and with a series of earlier HVOSM runs, which made use of inertial properties different from those of the test vehicle, was evaluated.

FOREWORD

This report summarizes the results of a research task directed toward further investigation of the correlation of Highway-Vehicle-Object Simulation Model (HVOSM) computer predictions of vehicle behavior with results of full-scale curb impact tests. The reported research, which constitutes one part of a Federal Highway Administration program entitled "Effectiveness of Geometric Design Criteria for Rural Highways," was performed under Subcontract Work Order No. 1, Task 2, Contract No. DOT-FH-11-9575. The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the Federal Highway Administration.

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1.0 INTRODUCTION

1.1 Background

In 1974, the National Cooperative Highway Research ~~Board~~ Program (NCHRP) awarded a research contract to the Texas Transportation Institute (TTI) to investigate vehicle responses to contacts with several different types of curbs (Reference 1). The research effort included the performance of eighteen full-scale tests using a 1963 Ford Galaxie and two different curb configurations. The Highway-Vehicle-Object Simulation Model (HVOSM) was then used to simulate the vehicle responses in the tests. Utilizing a film analysis technique, the results of the full-scale tests were compared with time-histories produced by the HVOSM simulation runs. The comparisons included the vehicle path after impact, the change in speed as a result of curb impact, and the vehicle elevation and ~~altitude~~ (i.e., roll, pitch, and vertical rise of a selected point on the front bumper with respect to the curb).

In the opinion of the authors of Reference 1, the results of these comparisons "agreed closely with the test results." On the basis of that finding, they proceeded to utilize HVOSM in a parametric investigation of four different types of curbs. The results of the parametric investigation served as the basis for recommendations in relation to the use of curbs.

1.2 Research Objectives

A detailed examination of the comparisons of full-scale test results with HVOSM simulations presented in Reference 1 reveals a number of response discrepancies. The simulated orientation and path of the vehicle after impact include significant deviations from the test results in many of the comparisons. Yet the cited comparisons constitute the "validation" of HVOSM for simulating vehicle responses in impacts with curbs.

In view of the fact that improper vehicle weights and suspension properties were used in the simulation study of Reference 1 (i.e., different from those of the test vehicle), the original limited objective of the presently reported research effort, as defined by Task B of Contract No. DOT-FH-11-9575, was to rerun the HVOSM simulation study of Reference 1 using the best available information for the actual weights and suspension properties of the test vehicle in the full-scale curb impact tests.

If significant differences were found in the correlation of HVOSM results with the full-scale tests, additional runs were planned to assess the validity of the parametric studies (i.e., for which no test results are available) and the subsequent conclusions with respect to curb utilization that are presented in Reference 1.

1.3 Organization of This Report

Conclusions and recommendations based on the results achieved within the reported research task are presented in Section 2.0. The results of the research are presented and discussed in Section 3.0. References are listed in Section 4.0.

The sources of parameter values for the simulation study are presented in Appendix A. A post-processing routine that was developed to calculate the position of a reference point on the front bumper is described in Appendix B.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

2.1.1 The correlation of the HVOSM response predictions with the full-scale test results of Reference 1 was improved by the following factors:

(1) The use, in the simulation, of inertial and suspension properties more representative of those of the test vehicle.

(2) Adjustment of the estimated steering system parameters on the basis of apparent steering system responses during the curb-impact tests of Reference 1. Note that neither the actual dynamic responses nor the actual parameters of the steering system were measured within the research program reported in Reference 1. However, the HVOSM runs for low-speed, shallow-angle curb contacts clearly included steering system effects greater than those that occurred in the corresponding test runs (i.e., the simulated steering system produced vehicle redirection that did not occur in the tests).

(3) The use, in the simulation, of vehicle parameters compatible with the unsymmetrical, energy-dissipating suspension bumpers that were incorporated in HVOSM in Reference 14 (1968). Note that on page 21 of Reference 1, the incomplete listing of input data includes a redundant definition of both symmetrical and unsymmetrical suspension

bumpers. Therefore, it is not clear which version of HVOSM and which of the two included definitions of the suspension bumpers was actually used.

2.1.2 The conclusions of Reference 1 regarding the usage and effectiveness of higher, barrier-type curbs, for which full-scale tests were not performed are based on simulation results of doubtful validity. The higher curbs can be expected to produce direct contact forces on the vehicle body (i.e., front bumper and undercarriage contacts) which could significantly affect the vehicle responses.

The HVOSM simulation study of Reference 1 and that reported herein do not include forces that act directly on the sprung mass of the vehicle. In addition to that source of errors, simulation runs replicating those reported in Reference 1, but making use of more representative vehicle parameters, do not include predicted pitch and roll responses of the large magnitudes documented in Reference 1. Thus, the simulation results of Reference 1 clearly cannot serve as a basis for valid conclusions regarding higher, barrier-type curbs.

2.1.3 For the vehicle speeds and approach angles included in this research, curbs with heights of six inches or less are not effective devices for achieving vehicle redirection. On the basis of the full-scale test results presented in Reference 1, and the simulation study reported herein, such curbs should not be installed for redirective purposes.

2.1.4 The detailed definition of the steering system plays an important role in the simulation of vehicle responses that occur in low-speed, shallow-angle impacts with curbs. Direct measurements of properties and of dynamic responses of steering systems in curb impacts should precede further simulation studies of vehicle impacts with curbs and/or curb-like obstacles (e.g., pavement edges adjacent to low shoulders).

2.2 Recommendations

2.2.1 A card image of HVOSM inputs should always be included in the documentation of application results. Also, the sources of the parameter data and the specific version of the HVOSM program should be defined.

Many of the difficulties encountered in the performance of this research could have been avoided if Reference 1 had included a complete definition of the vehicle parameters used in the simulation studies. Also, the specific version of HVOSM is obscured by the fact that redundant and incompatible definitions of the suspension bumper clearances are included in the incomplete listing of input data on page 21 of Reference 1 (i.e., OMEGAF, OMEGFC, OMEGFE and OMEGAR, OMEGRC, OMEGRE). As a result of the incomplete definition of inputs, a substantial effort was required to retrace the probable parameter values used.

Several versions of HVOSM are available and, as discussed in Appendix A, a number of modifications of simulation details as well as input parameter definitions have been made.

2.2.2 The auxiliary computer-graphics display capability of HVOSM should be utilized to investigate possible violations of simplifying assumptions in applications where potential problems can be anticipated (e.g., the assumption that no forces act directly on the sprung mass).

The graphics program was developed to ease the task of critically reviewing the detailed three-dimensional motions predicted for a simulated vehicle, particularly where interferences with fixed obstacles may occur. In the HVOSM runs of Reference 1 that are related to the 13 inch high, type X curb, the neglect of probable contact forces that would act directly on the sprung mass during a traversal of the curb raises serious doubts regarding the validity of the predicted trajectories. Interferences between the sprung mass and the 13 inch high curb would have been revealed by computer graphics displays.

2.2.3 The adequacy of the existing, thin-disc representation of the tires and wheels for simulation of shallow-angle contacts with curbs and/or curb-like obstacles (e.g., pavement edges adjacent to low shoulders) should be critically evaluated by means of detailed comparisons of response predictions with test results using an instrumented vehicle.

In shallow-angle contacts with curbs, contact forces on the tire sidewalls and the wheel rims may play a major role in determining the responses of the steering system and of the overall vehicle. The existing thin-disc form of tire/wheel simulation generates side forces through the mechanism of slip angles only. Thus, minor extensions of HVOSM may be found necessary to produce valid response predictions in shallow-angle curb contacts.

2.2.4 Users of HVOSM should be made aware of changes in the definitions of some inputs to the HVOSM version defined in Reference 9 for which the symbols of earlier versions of the program have been retained. In particular, the coefficients of cubic terms in the suspension bumper force calculations were previously multiplied by the coefficients of the linear terms. In Reference 9, brackets within the force equations were removed and the multiplication of the two separate coefficients was thereby eliminated. Also, inputs for friction coefficients in the HVOSM version defined in Reference 9 are applied as multiplication factors for the nominal tire-terrain friction coefficient, whereas in earlier versions of the program the inputs were applied directly as friction coefficients. The cited changes in input definitions are discussed in Appendix A.

3.0 DISCUSSION OF RESULTS

Revisions were made in the HVOSM inputs defining the simulated vehicle to more closely match the test vehicle (see Appendix A), and the simulations of the eighteen full-scale tests were repeated. Significant improvements were found to be produced in the correlation between the simulations and the full-scale test results for high-speed, large encroachment angle runs (see Figures 1 through 4*). However, important discrepancies remained in the correlation between the low-speed, shallow angle full-scale tests and the corresponding simulation runs.

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*Note that the presented figures are enlargements of figures from Reference 1 with the revised HVOSM results superimposed.

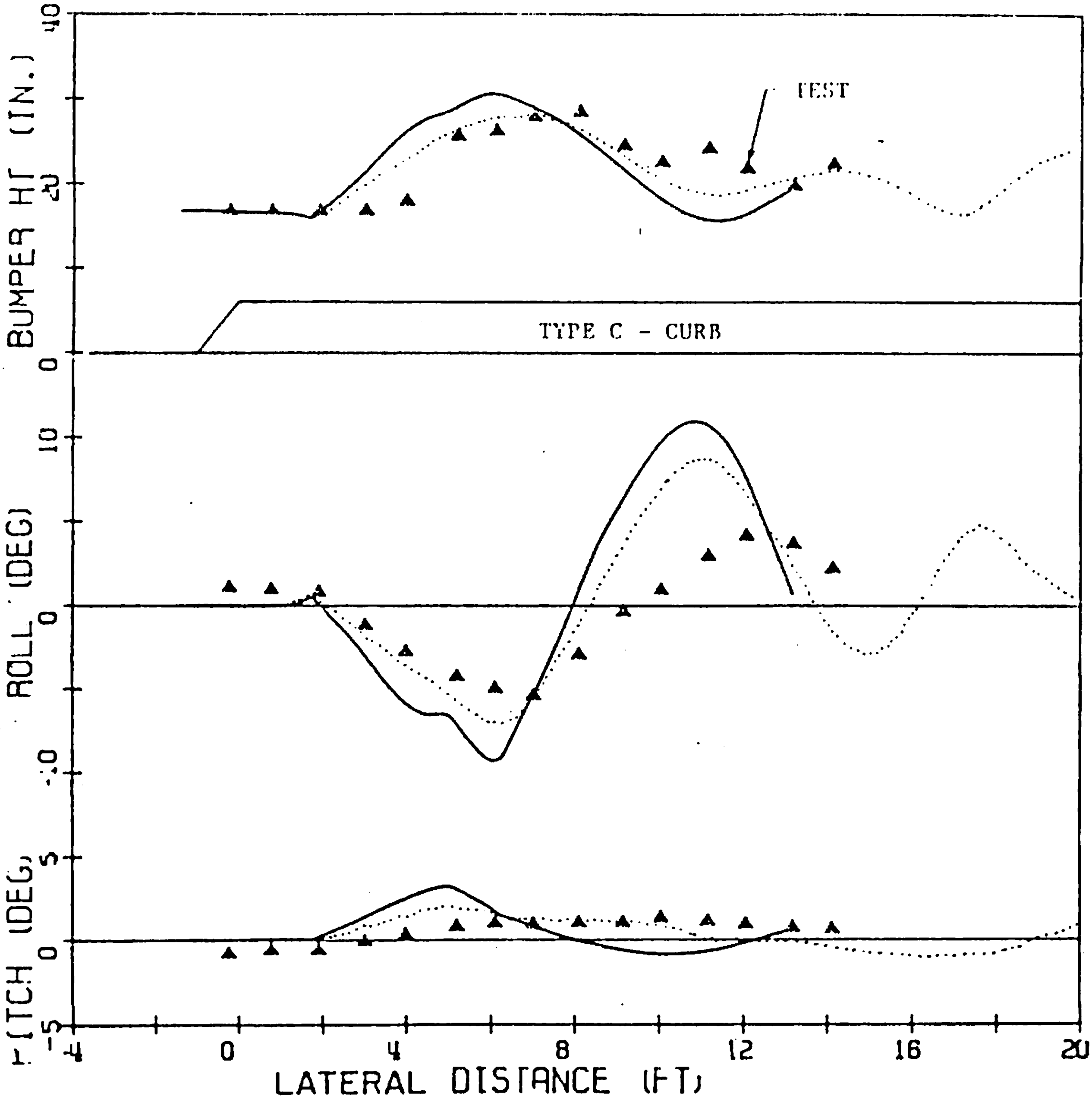


Figure 1. Test No. N-16.

43.0 MPH
18.4 DEG
Curb Type C

······· MCI HVOSM
——— REF 1 HVOSM
▲ REF 1 TEST

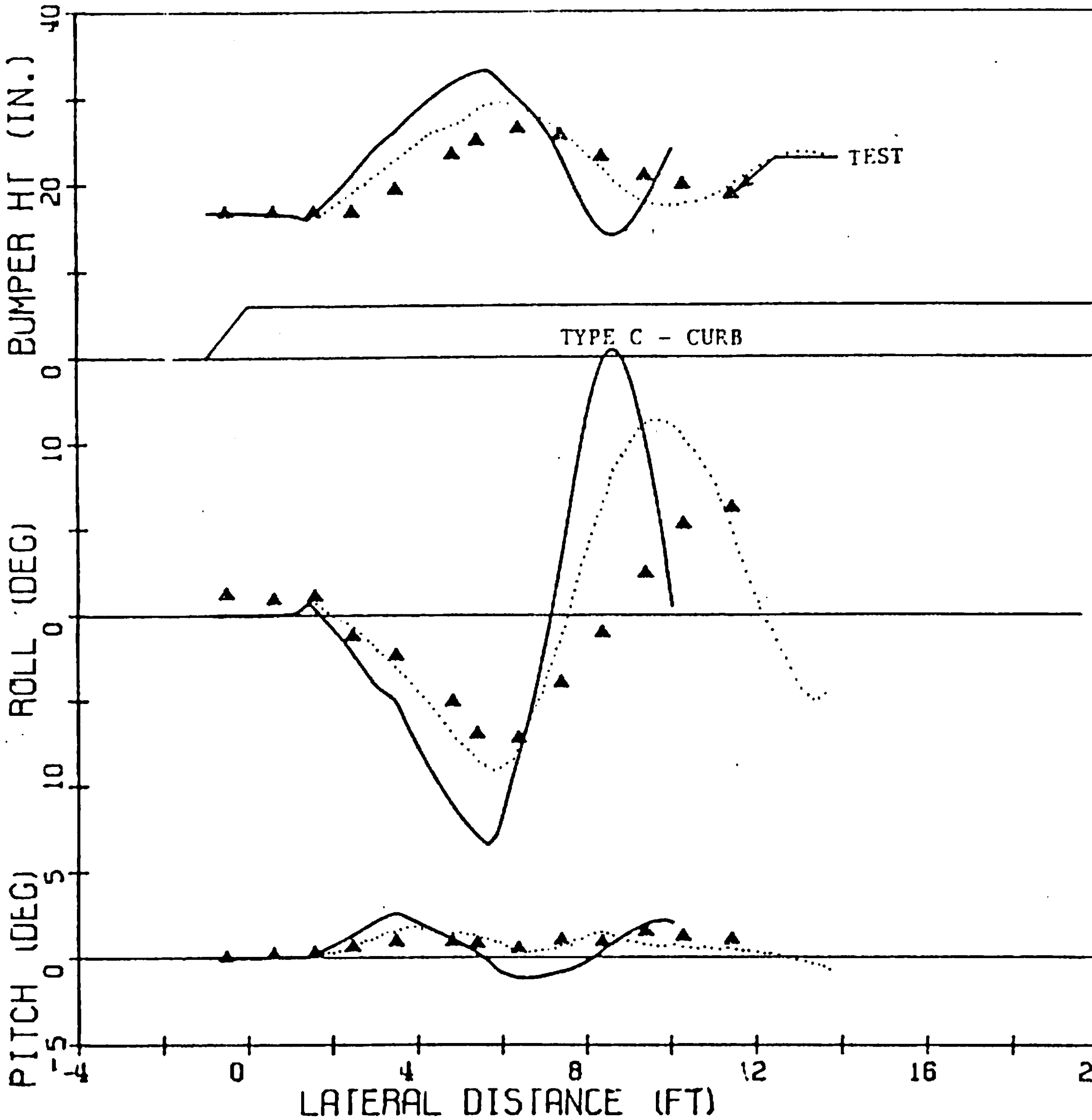


Figure 2. Test No. N-18.

62.2 MPH
12.3 DEG
Curb Type C

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

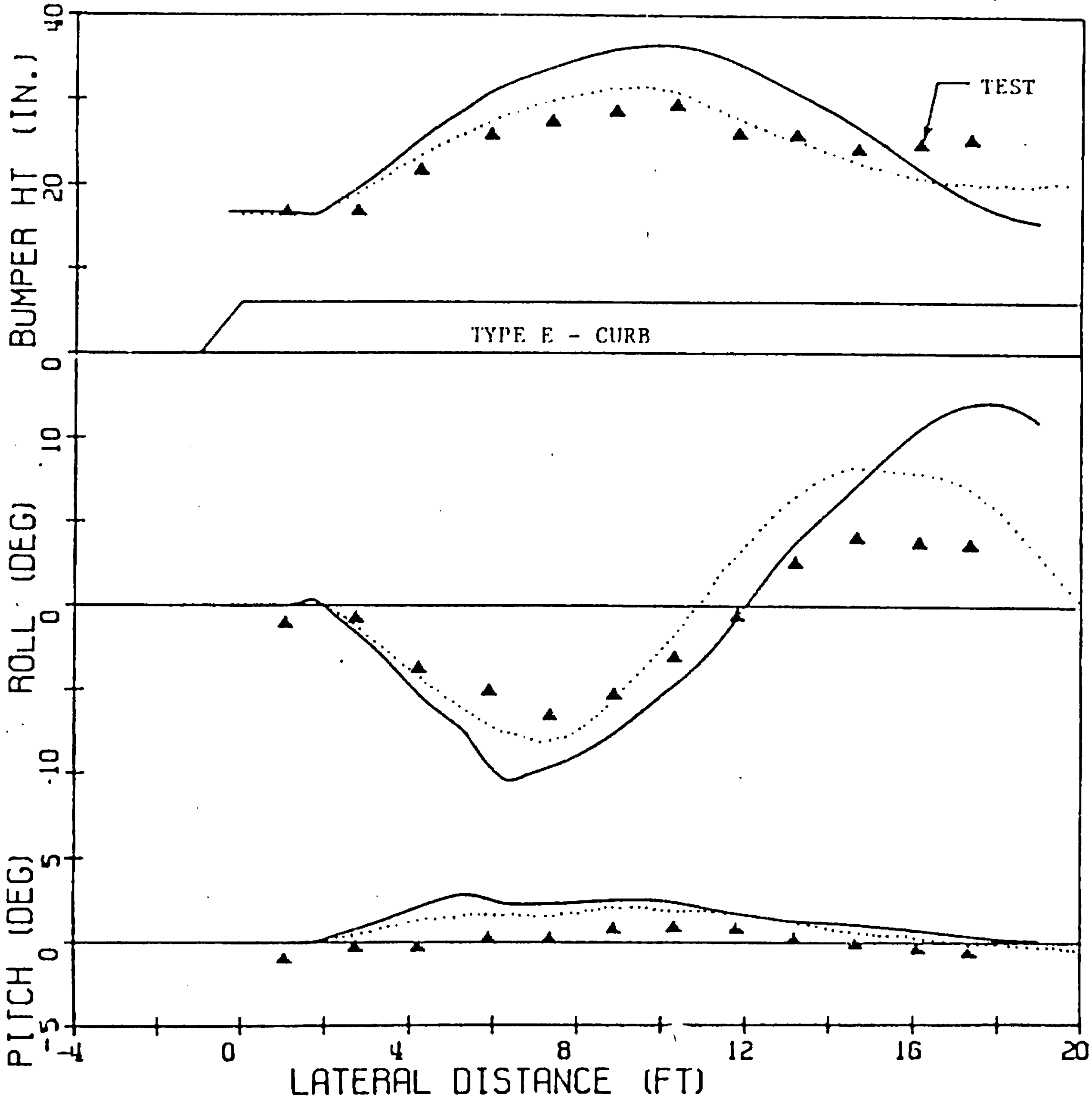


Figure 3. Test No. N-10.

63.0 MPH
17.6 DEG
Curb Type E

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

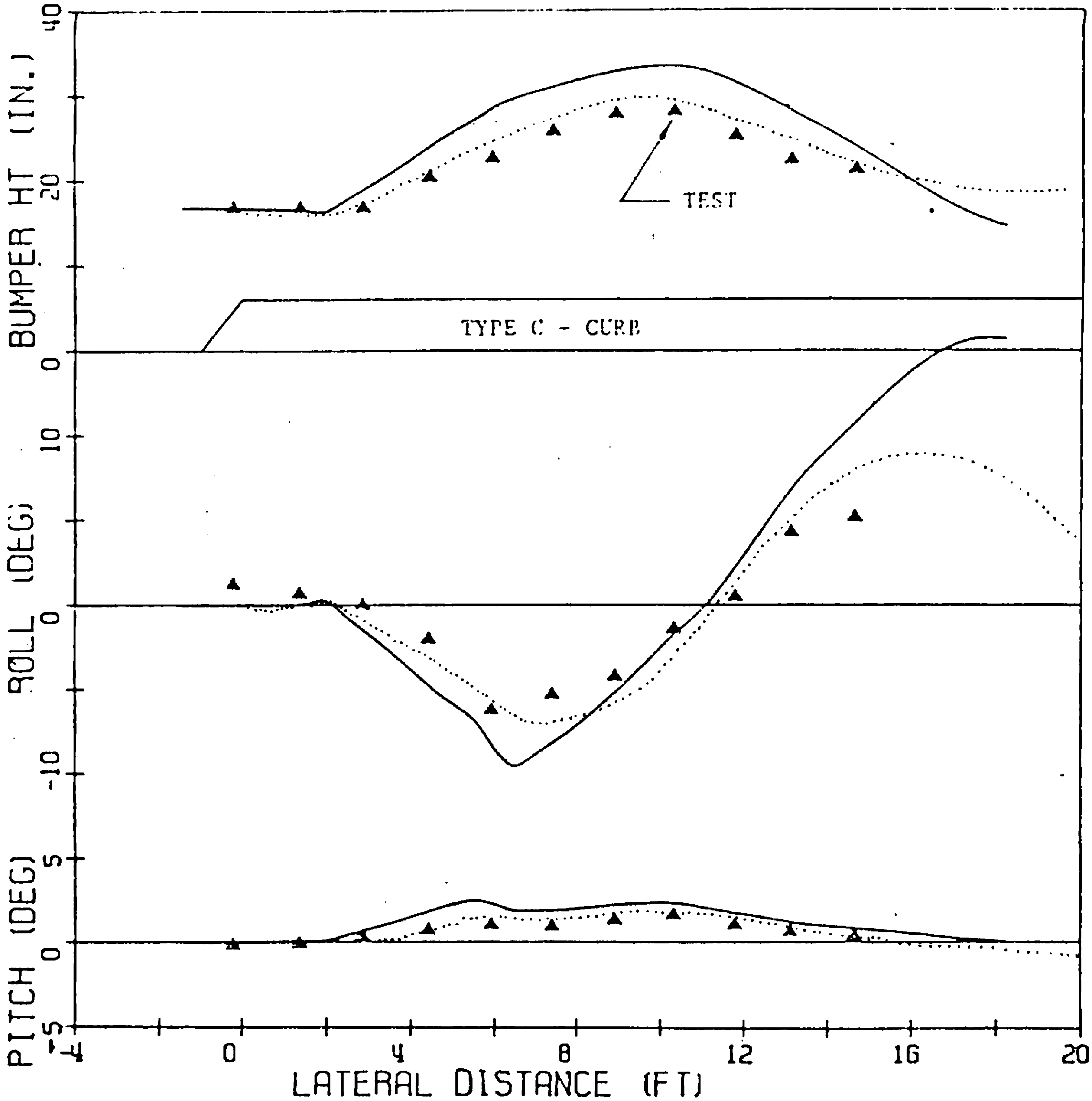


Figure 4. Test No. N-19.

61.5 MPH
18.6 DEG
Curb Type C

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

The form of documentation of the full-scale test results in Reference 1 consists of graphs and a brief description. One difficulty with the documentation of the test results in Reference 1 is that, in some instances for the low-speed, shallow angle curb contacts, the descriptions and graphs of the tests do not appear to agree. For example, the descriptions of full-scale tests N-2 and N-11 contained in Table 2 of Reference 1 indicate that the vehicle was redirected. Yet the corresponding plots in Appendix D of Reference 1 indicate that the test vehicle did not deviate significantly from its initial heading and that the bumper point reached a lateral distance of approximately four feet, not indicative of redirection. (See Figures 5 through 8.)

The residual discrepancies between the test results and the simulation runs may reflect effects of analytical inaccuracies in the tire force and steering system aspects of HVOSM (see Recommendations, sec. 2.2). However, they may also reflect errors inherent in the research techniques employed in Reference 1, such as:

(1) Reference 1 contains no clear definition of redirection.

(2) The film analysis procedure utilized in Reference 1 for documenting the full-scale tests employed a Vanguard Motion Analyzer which required the use of two fixed ground reference points. The initial point was defined in Reference 1 to correspond to the instant at which the tire was on top of the curb, which "was not well defined" (Ref. 1) and "hence, some error was introduced in the film data" (Ref. 1). The final ground reference point was defined as "a time at which the vehicle came to a stable attitude" (Ref. 1). Note that many of the plots of the full-scale

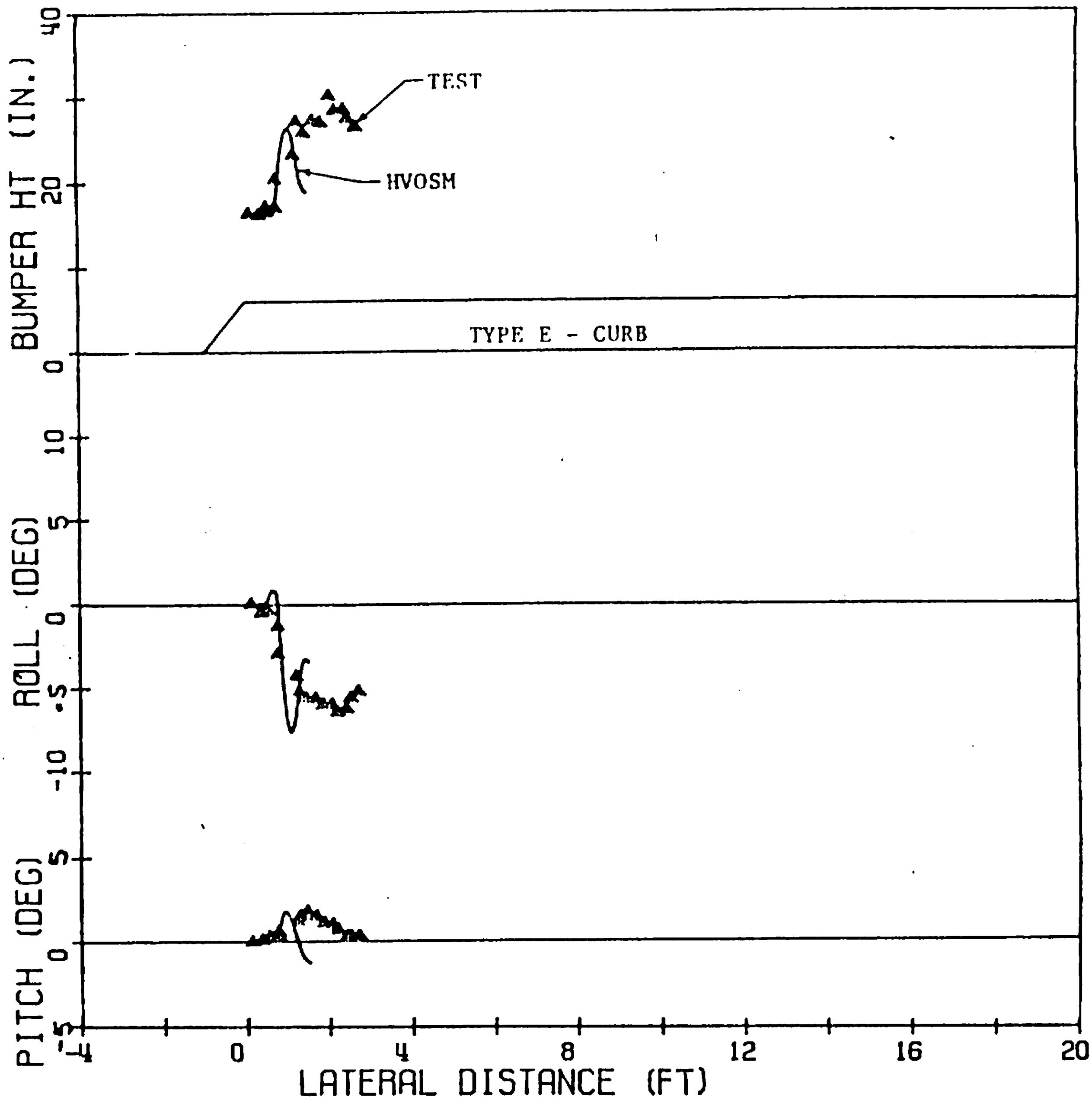


Figure 5. Full-scale test described in Ref. 1 to be "redirected."

Test No. N-2

30.4 MPH
5.1 DEG
Curb Type E

— REF 1 TEST
▲ REF 1 HVOSM

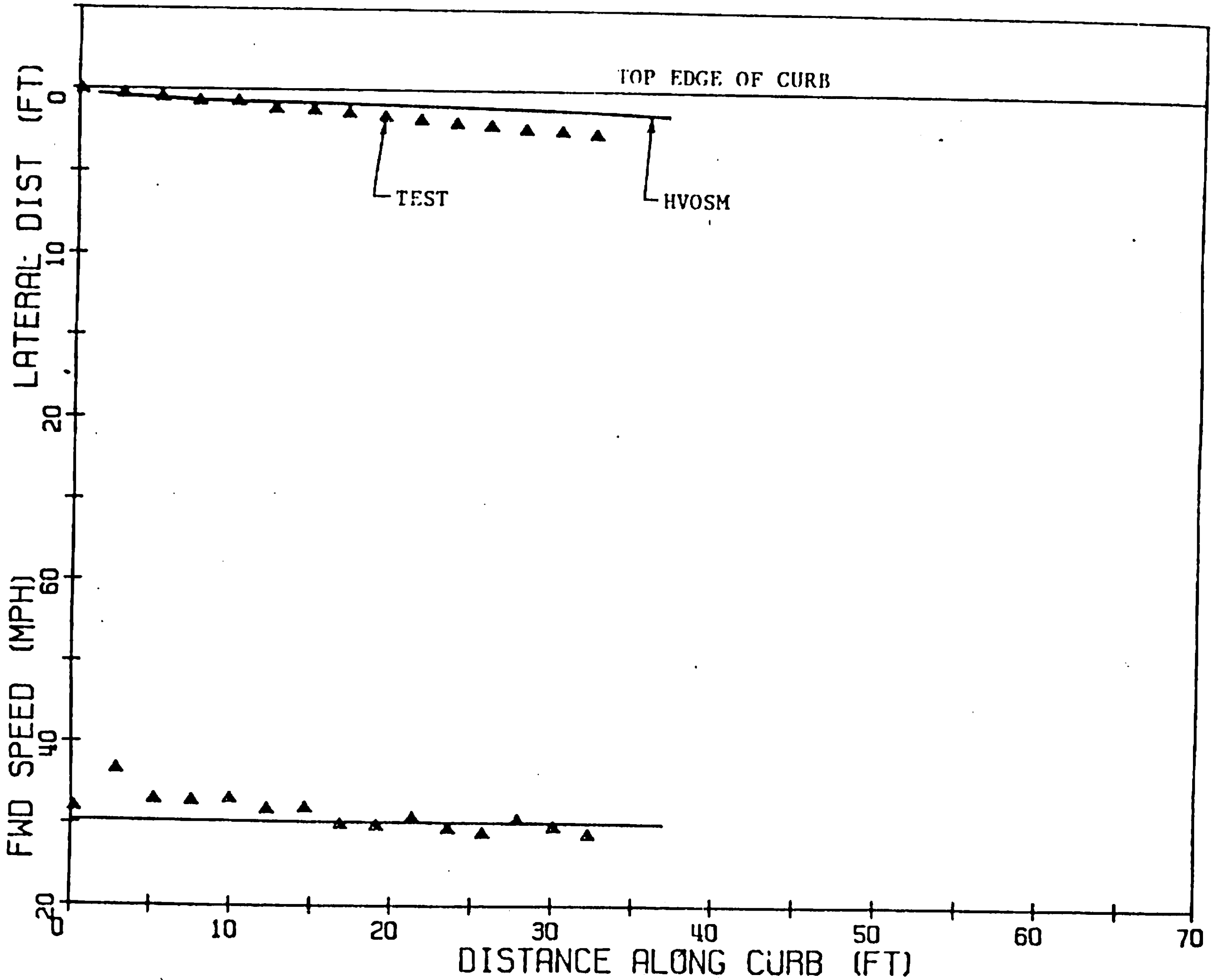


Figure 6. Test No. N-2 (Cont'd)

— REF 1 TEST
▲ REF 1 HVOSM

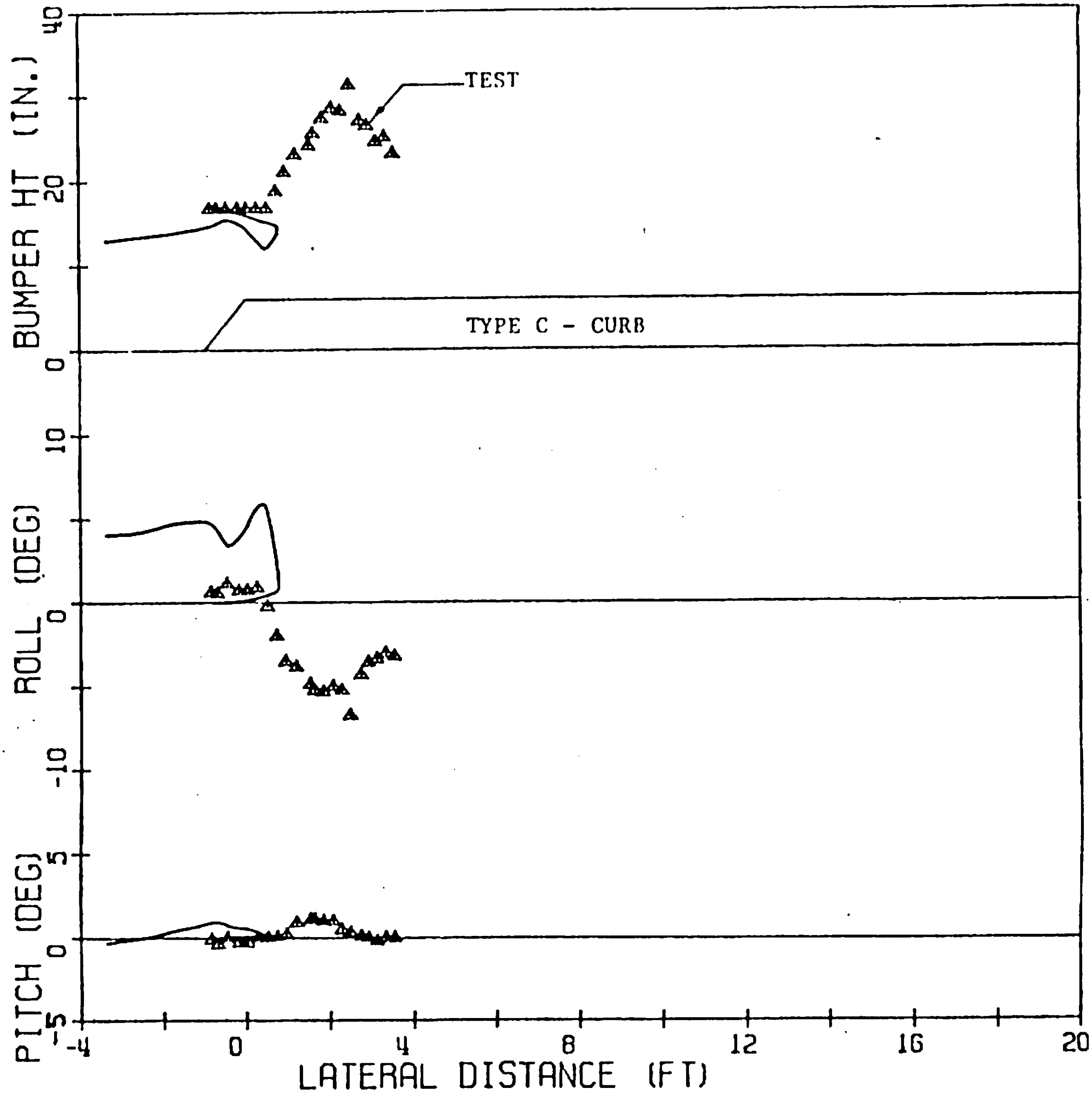


Figure 7. Full-scale test described in Ref. 1 to be "redirected smoothly."

Test No. N-11

34.2 MPH
4.9 DEG
Curb Type C

— REF 1 TEST
▲ REF 1 HVOSM

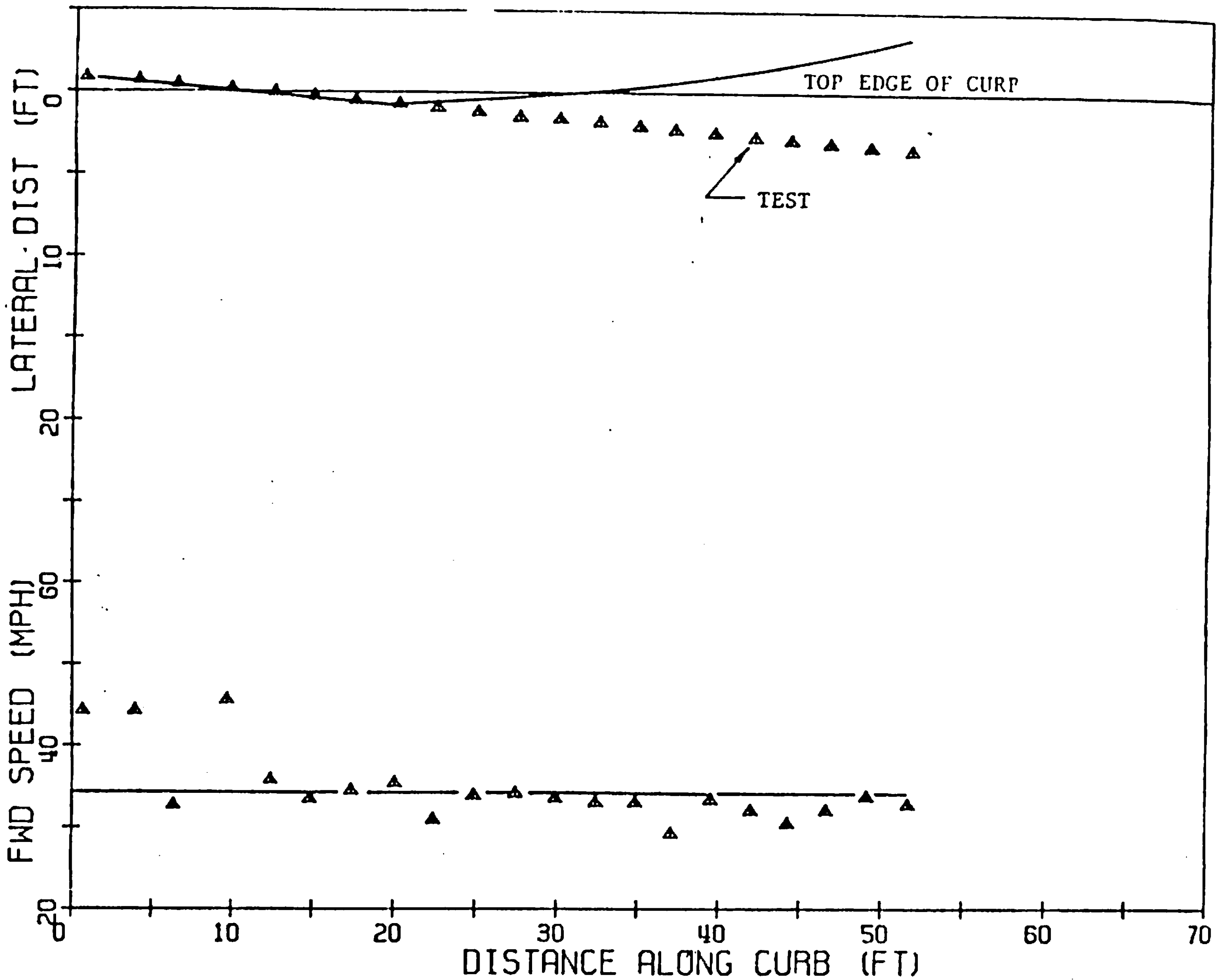


Figure 8. Test No. N-11 (Cont'd)

— REF 1 TEST
▲ REF 1 HVOSM

test results in Reference 1 end when the vehicle is still in an unstable position (i.e., vehicle still has an appreciable roll and pitch attitude; see Figures 9 and 10).

(3) The assumption was made, as part of the film analysis technique employed in Reference 1, that the vehicle had negligible roll and pitch angles when its tire was on top of the curb (i.e., the initial point for analysis). In many instances this assumption may have been in error.

(4) The film analyses in Reference 1 involved different film speeds for the parallel and perpendicular cameras. Synchronization of two cameras with the same nominal speed presents difficulties as a result of motor and shutter speed performance fluctuation and degradation. The use of cameras with different nominal speeds compounds the synchronization problems and increases the probability of errors.

The cited problems in the photographic techniques used in analyzing the full-scale tests of Reference 1 would be somewhat greater for the low-speed, shallow angle curb impacts where:

(a) the initial and final reference points are not well defined (i.e., a tire may scrub for some distance prior to mounting the curb).

(b) the pitch and roll angles of the vehicle would be generally larger when the tire is initially on top of the curb (i.e., the elapsed time during curb mounting permits larger angular responses).

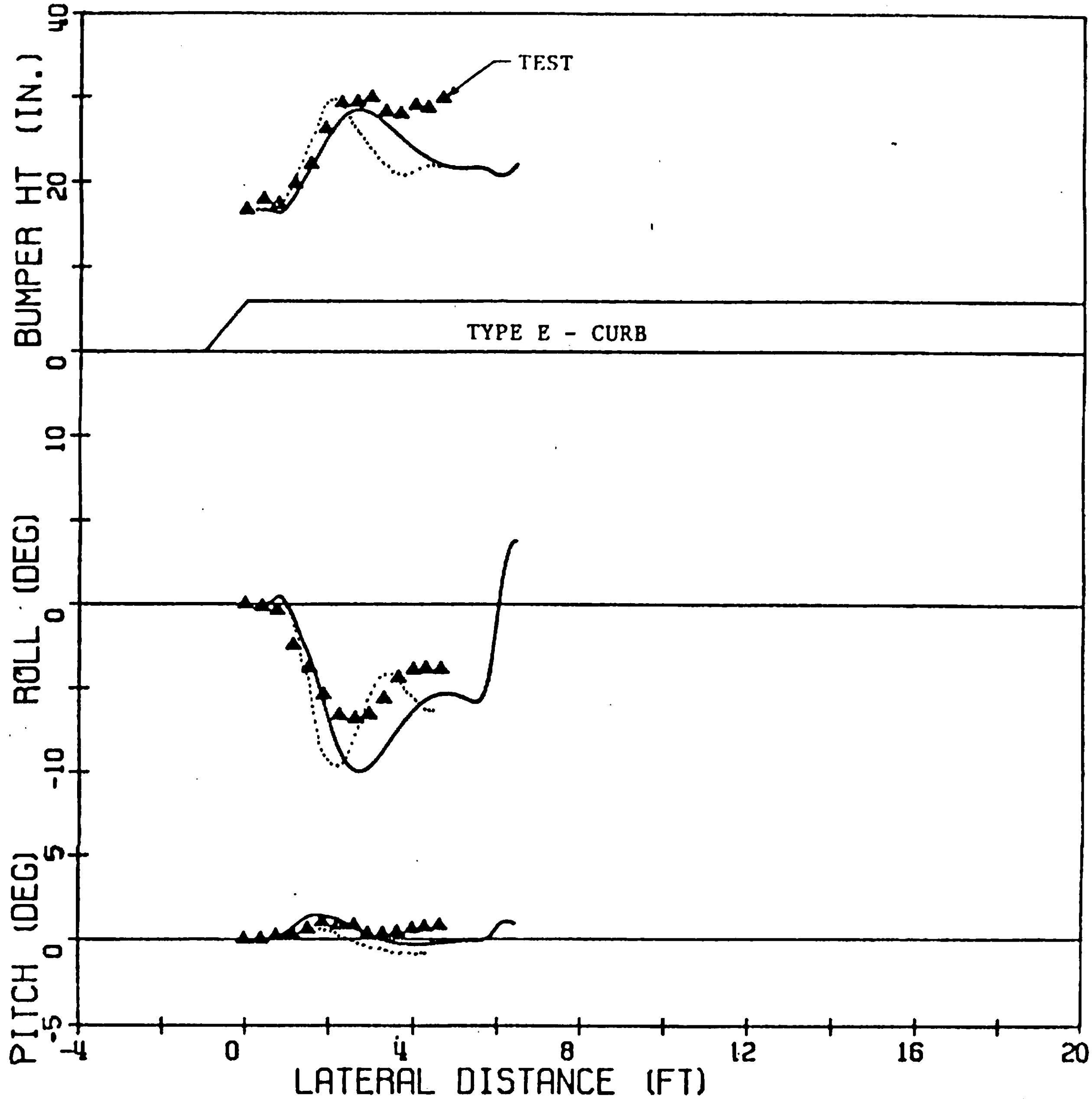


Figure 9. Test vehicle with roll and pitch and end of documentation of full-scale test.

Test No. N-4

59.3 MPH
4.6 DEG
Curb Type E

— REF 1 HVOSM
▲ REF 1 TEST

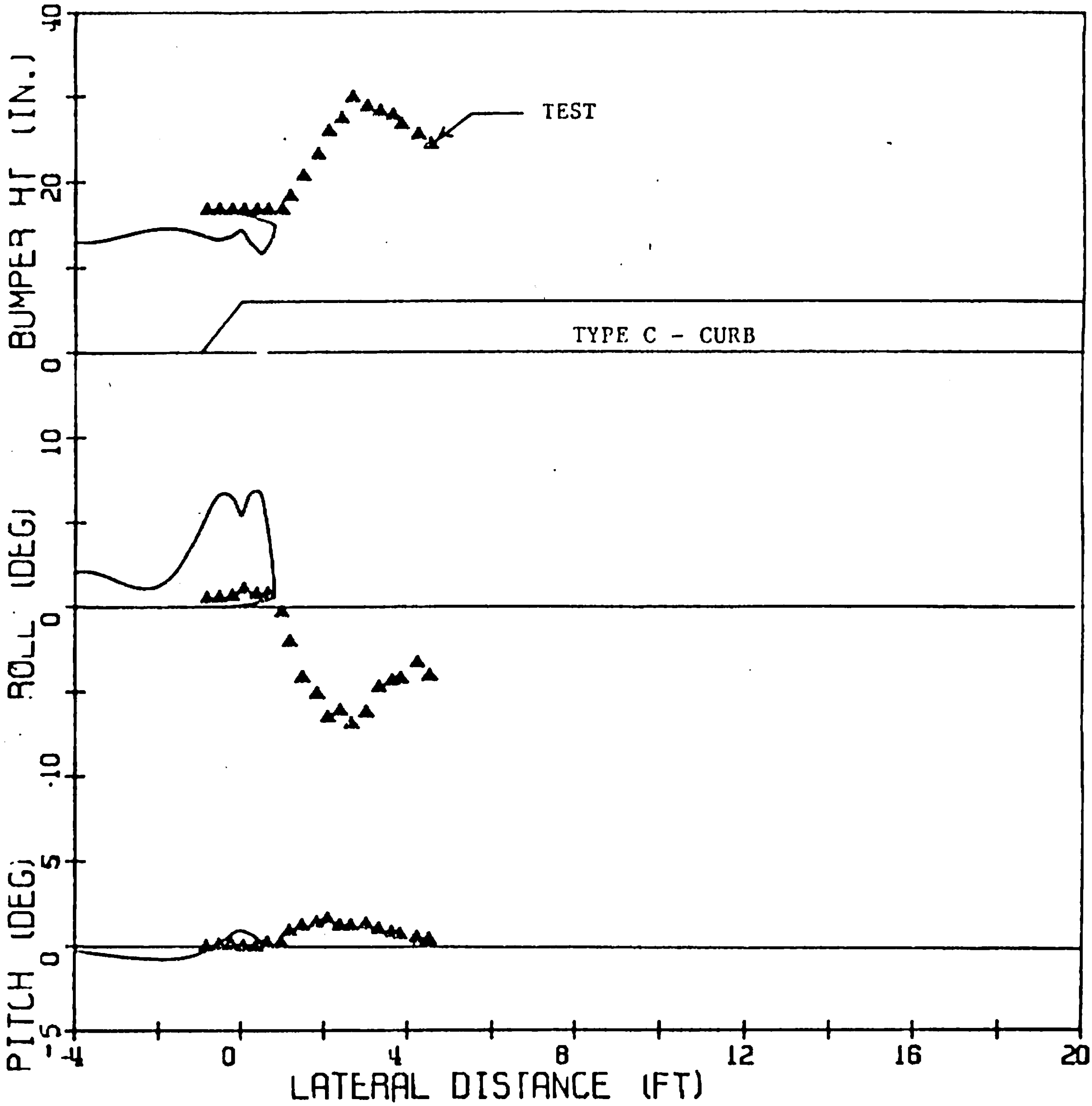


Figure 10. Test vehicle with roll and pitch at end of documentation of full-scale test.

Test No. N-12

44.7 MPH
5.1 DEG
Curb Type C

—— REF 1 HVOSM
▲ REF 1 TEST

(c) the changes in position of the vehicle between frames is at a minimum (i.e., the reference point definitions are more critical).

In spite of the cited shortcomings of the photographic analysis technique that was used in Reference 1, it is apparent that the HVOSM responses indicated substantially greater vehicle redirection than the full-scale test results in the low-speed, shallow angle curb impacts. The predictions by HVOSM of redirection of the vehicle from its initial path involved large steer angles produced by the curb contacts on the front wheels. The parameter values used for the steering system in Reference 1 were estimates that were made during early HVOSM development. The research program reported in Reference 1 did not include measurement of steering system parameters or recording of actual steering system responses in the tests. In view of the cited important discrepancies between predicted and measured redirection responses of the vehicle and also the use of estimated steering system parameters, adjustment of the estimated values appeared to be justified.

Exploratory simulation runs were performed to test the sensitivity of the redirection responses to changes in the steering system properties. Increasing the steering system constraint represented as coulomb friction (CPSP) had a favorable effect on the correlation of predicted and measured vehicle responses in the low-speed, shallow angle impacts.

The simulations of the eighteen full-scale tests were repeated using the revised value of the steering system constraint (i.e., coulomb friction) and a general improvement in correlation was found in most of the simulations. (See Figures 11 through 26.)

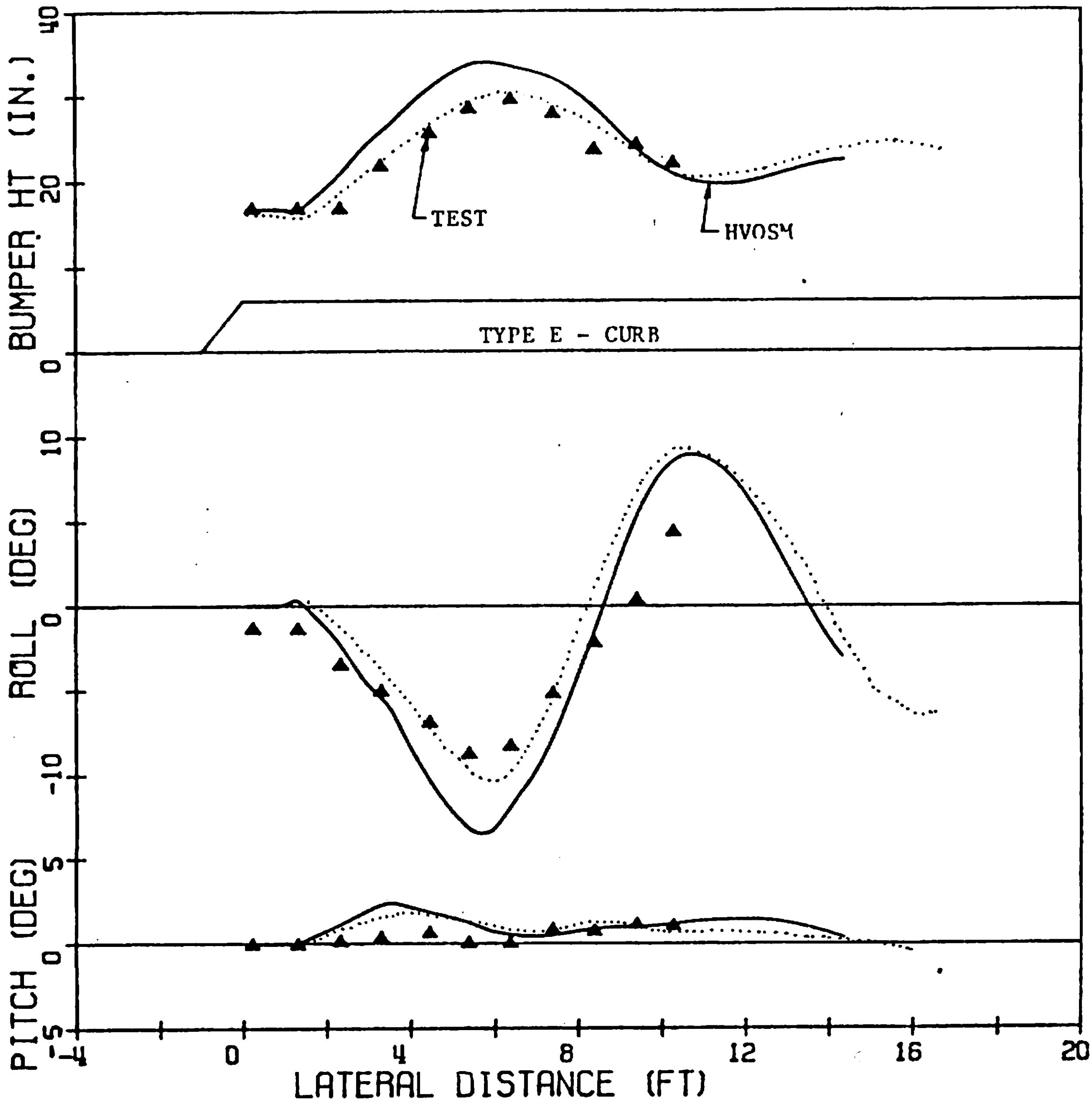


Figure 11. Test No. N-7.

63.6 MPH
12.6 DEG
Curb Type E

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

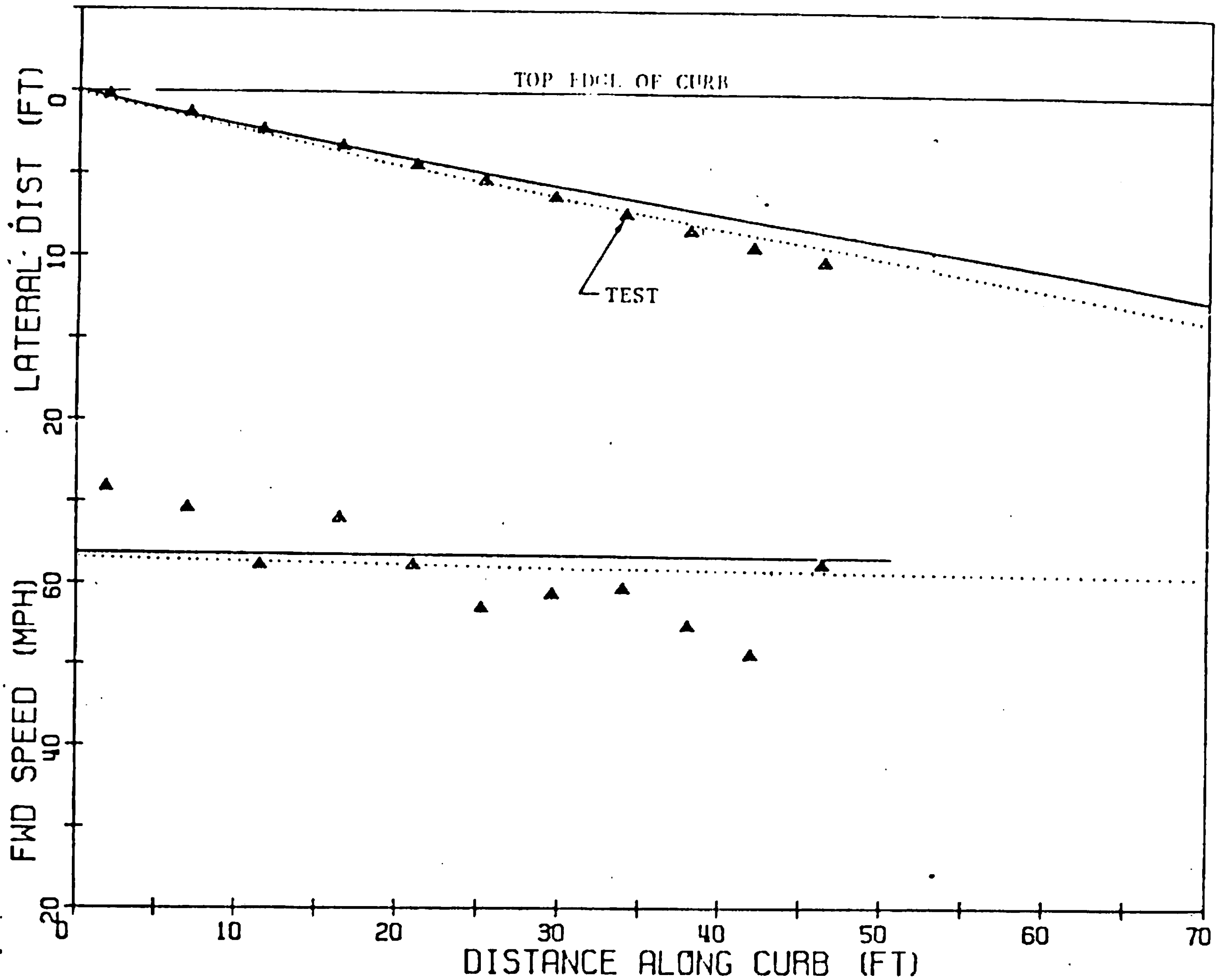


Figure 12. Test No. N-7 (Cont'd).

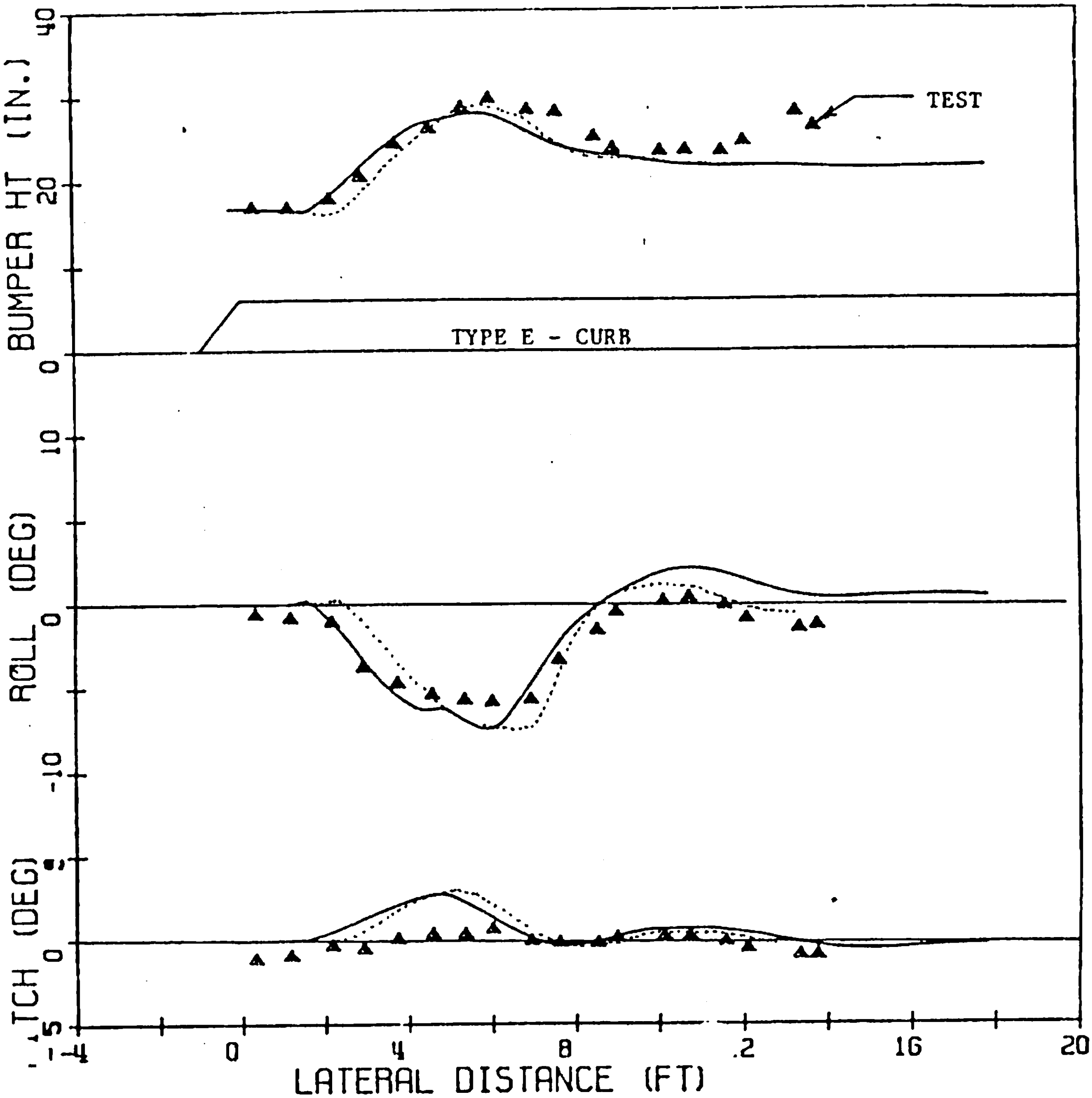


Figure 13. Test No. N-8.

32.7 MPH
18.5 DEG
Curb Type E

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

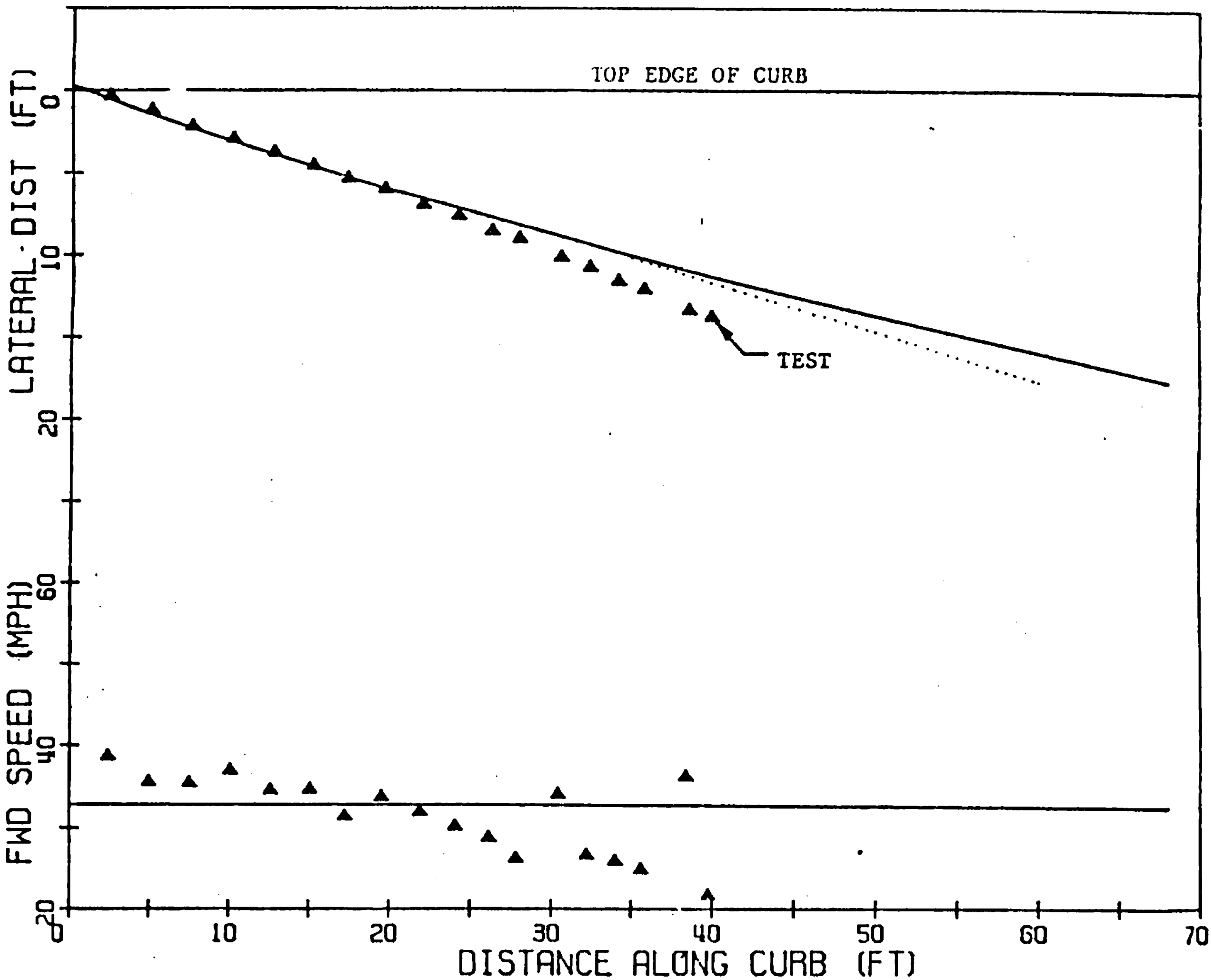


Figure 14. Test No. N-8 (Cont'd).

MCI HVOSM
REF 1 HVOSM
REF 1 TEST

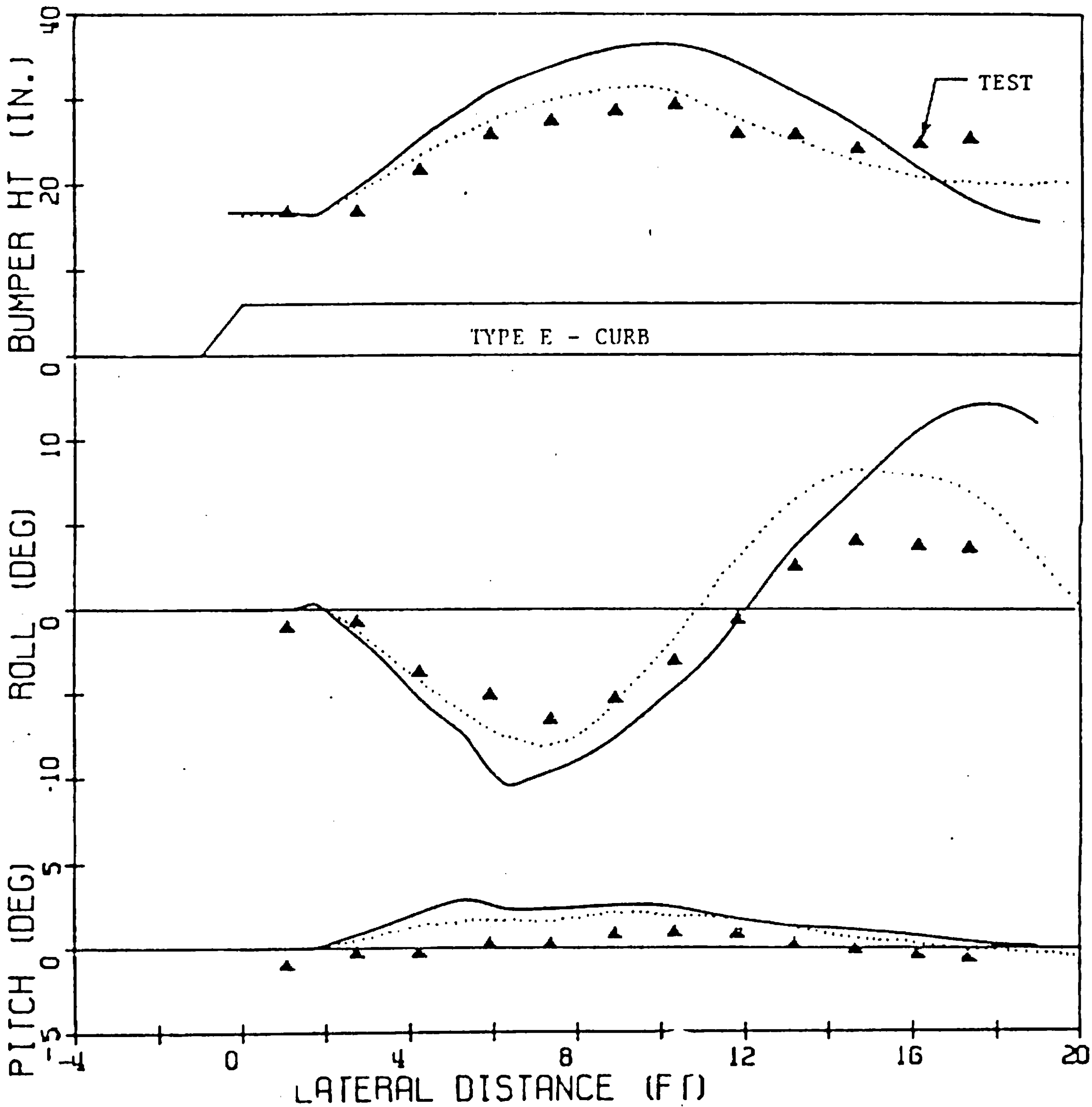


Figure 15. Test No. N-10.

63.0 MPH
17.6 DEG
Curb Type E

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

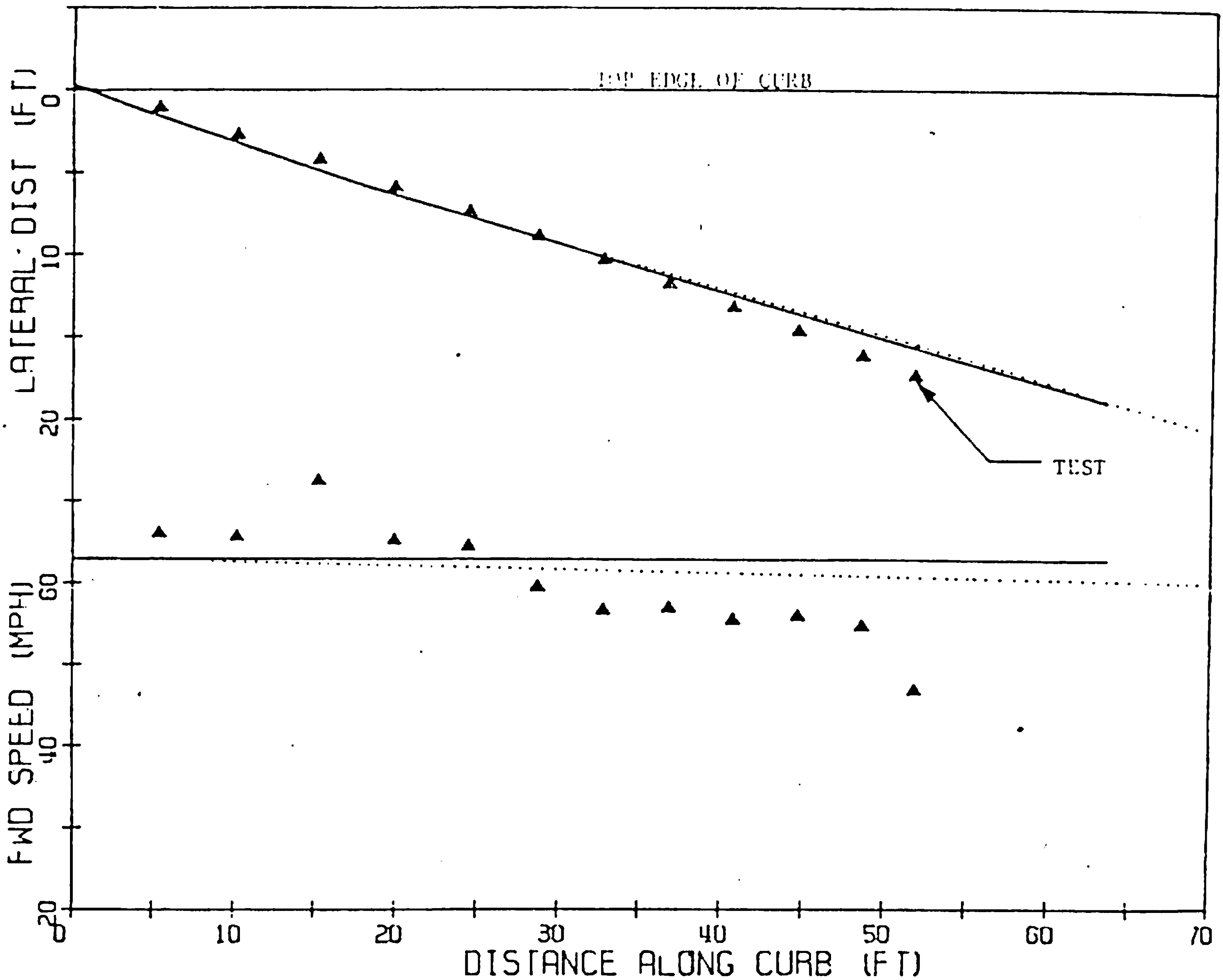


Figure 16. Test No. N-10 (Cont'd).

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

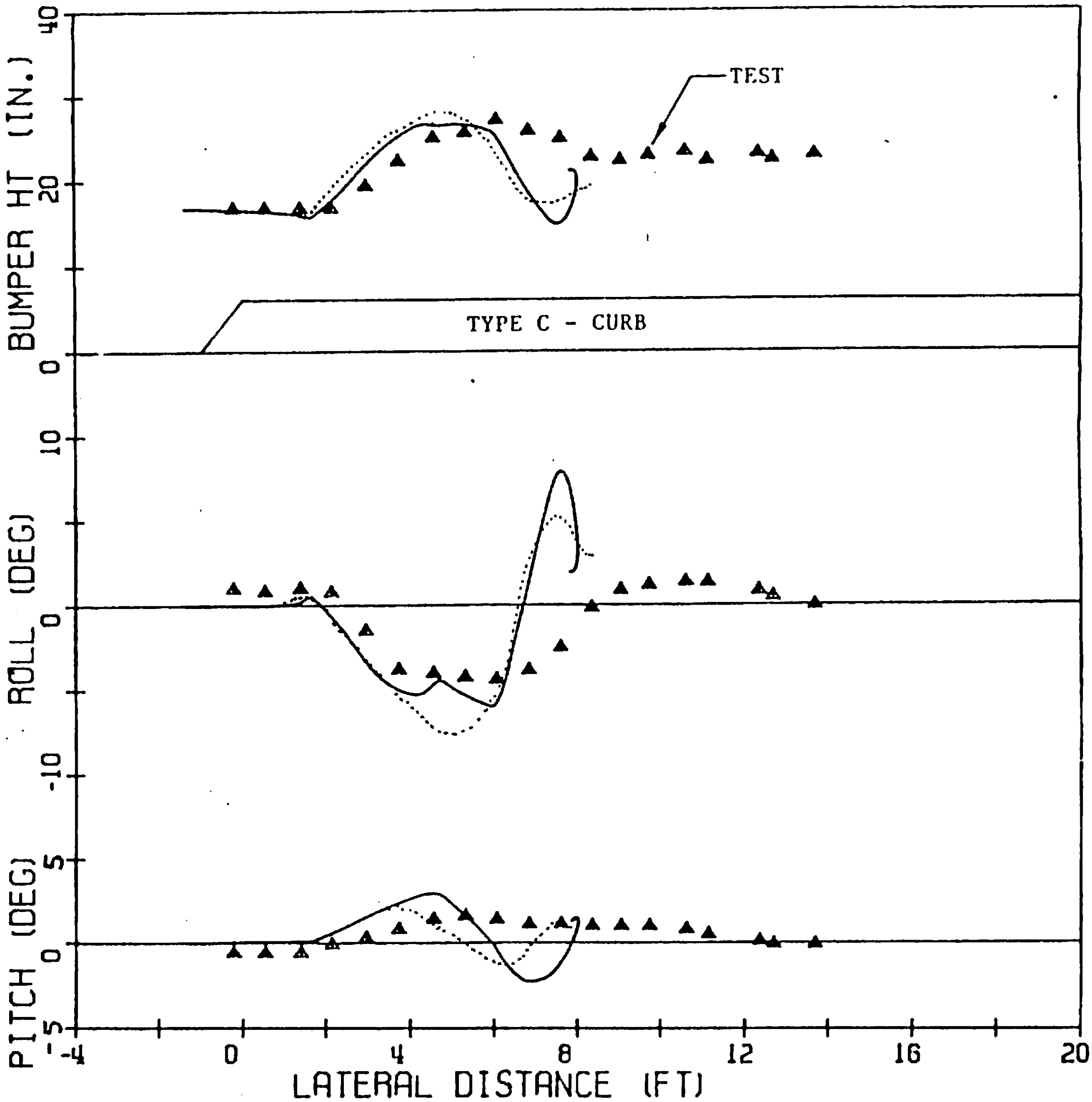


Figure 17. Test No. N-14.

43.5 MPH
12.8 DEG
Curb Type C

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

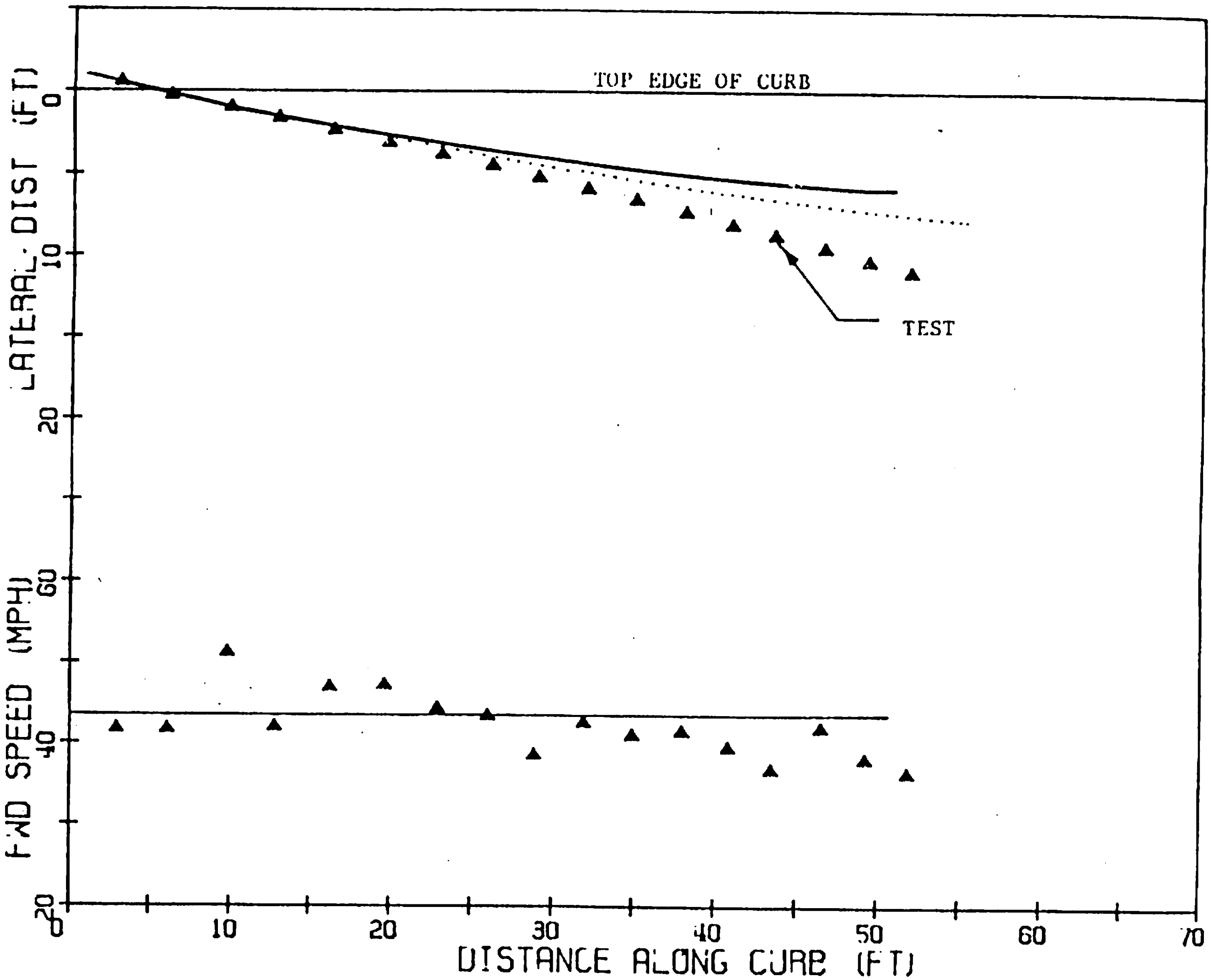
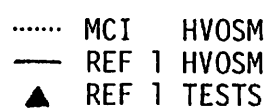


Figure 18. Test No. N-14 (Cont'd).



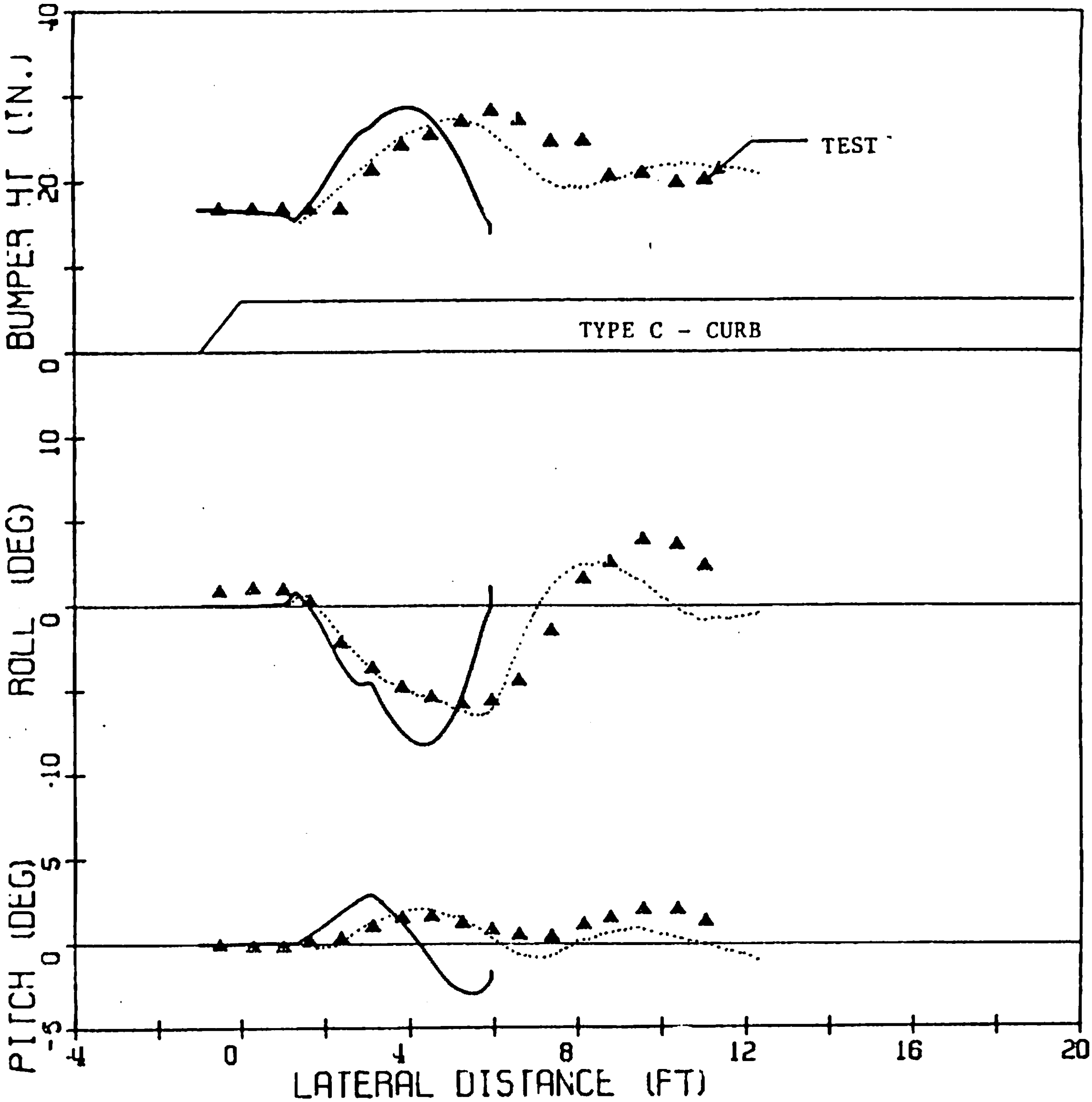


Figure 19. Test No. N-15.

32.1 MPH
17.4 DEG
Curb Type C

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TESTS

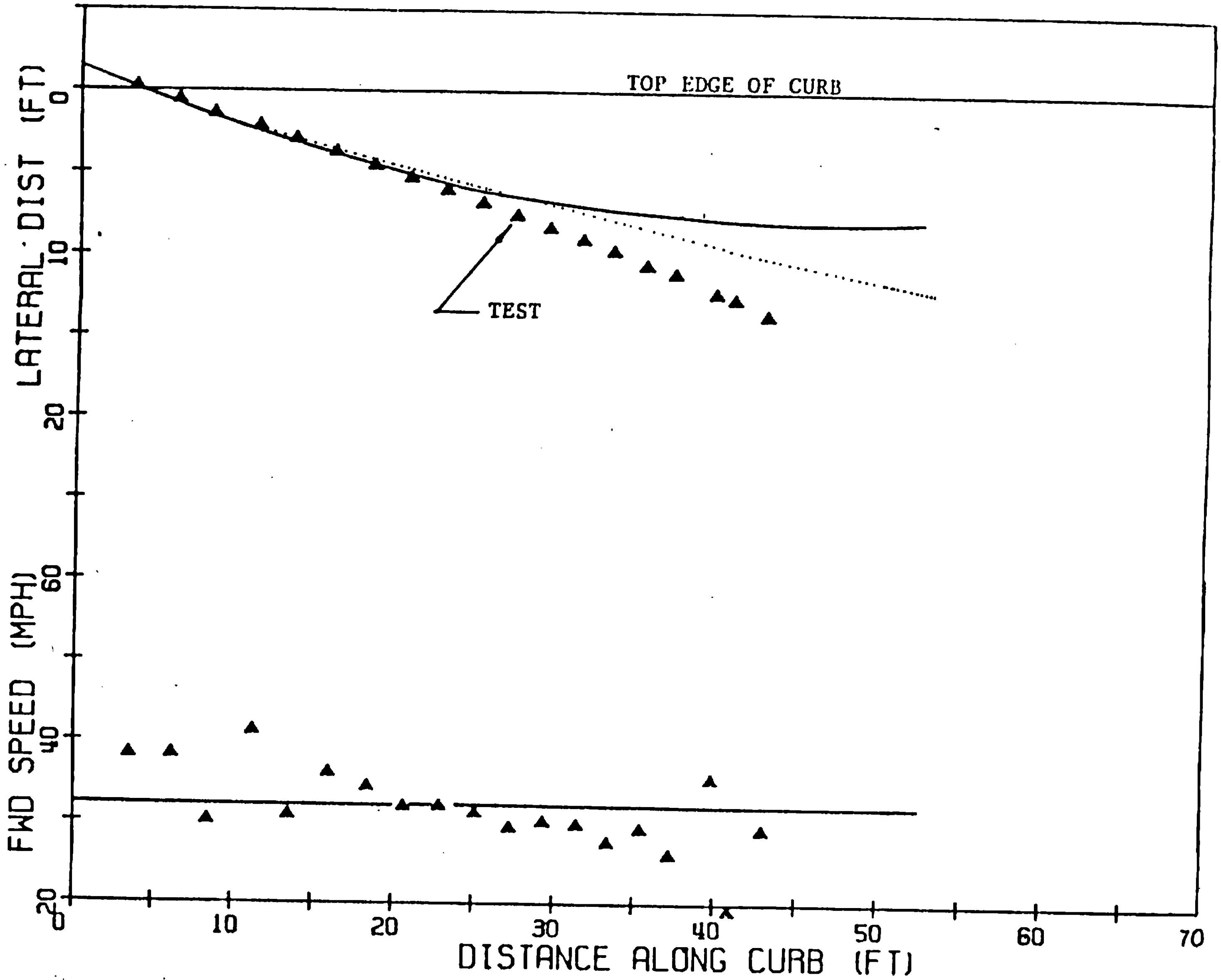


Figure 20. Test No. N-15 (Cont'd).

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TESTS

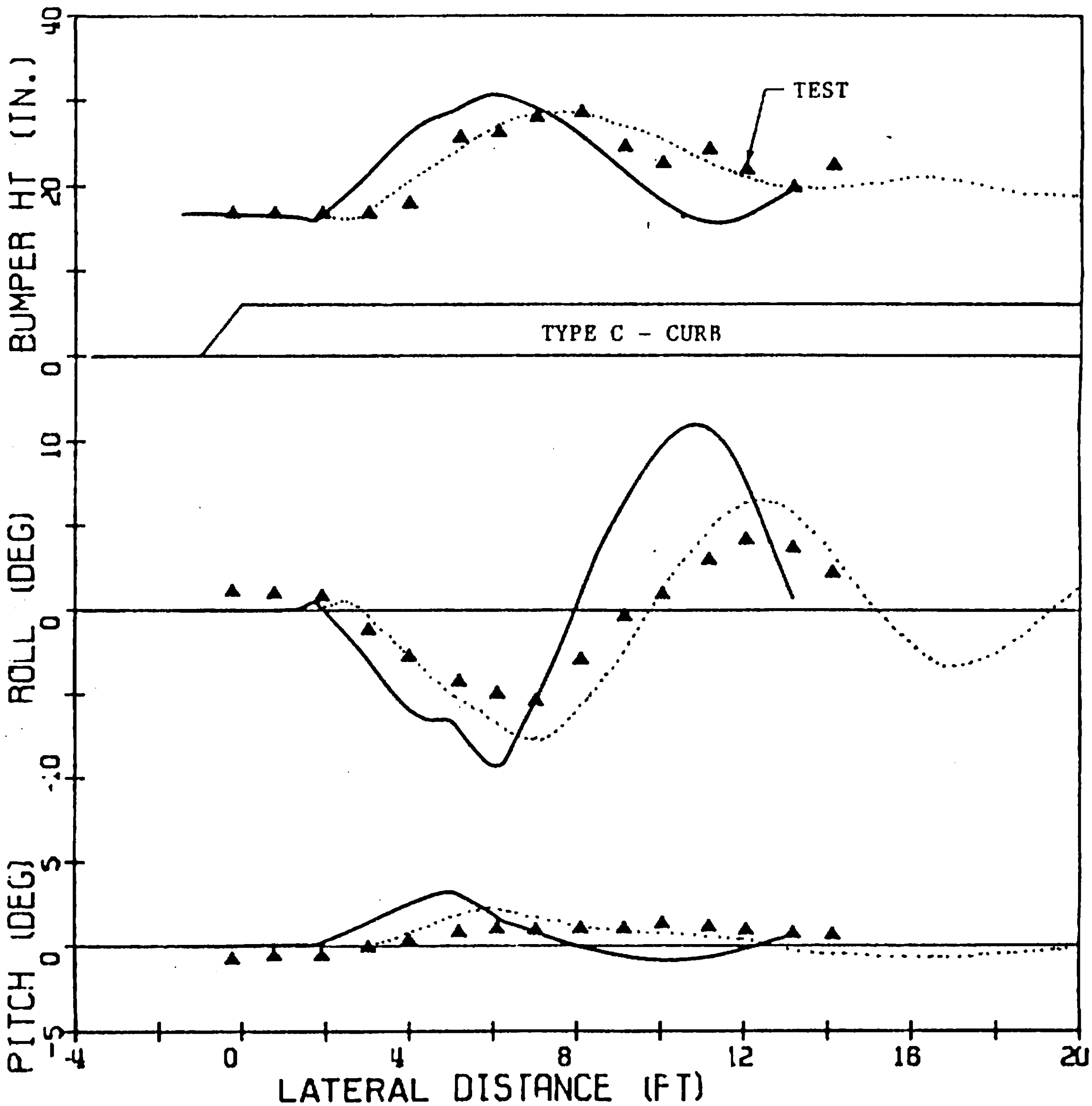


Figure 21. Test No. N-16.

43.0 MPH
18.4 DEG
Curb Type C

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

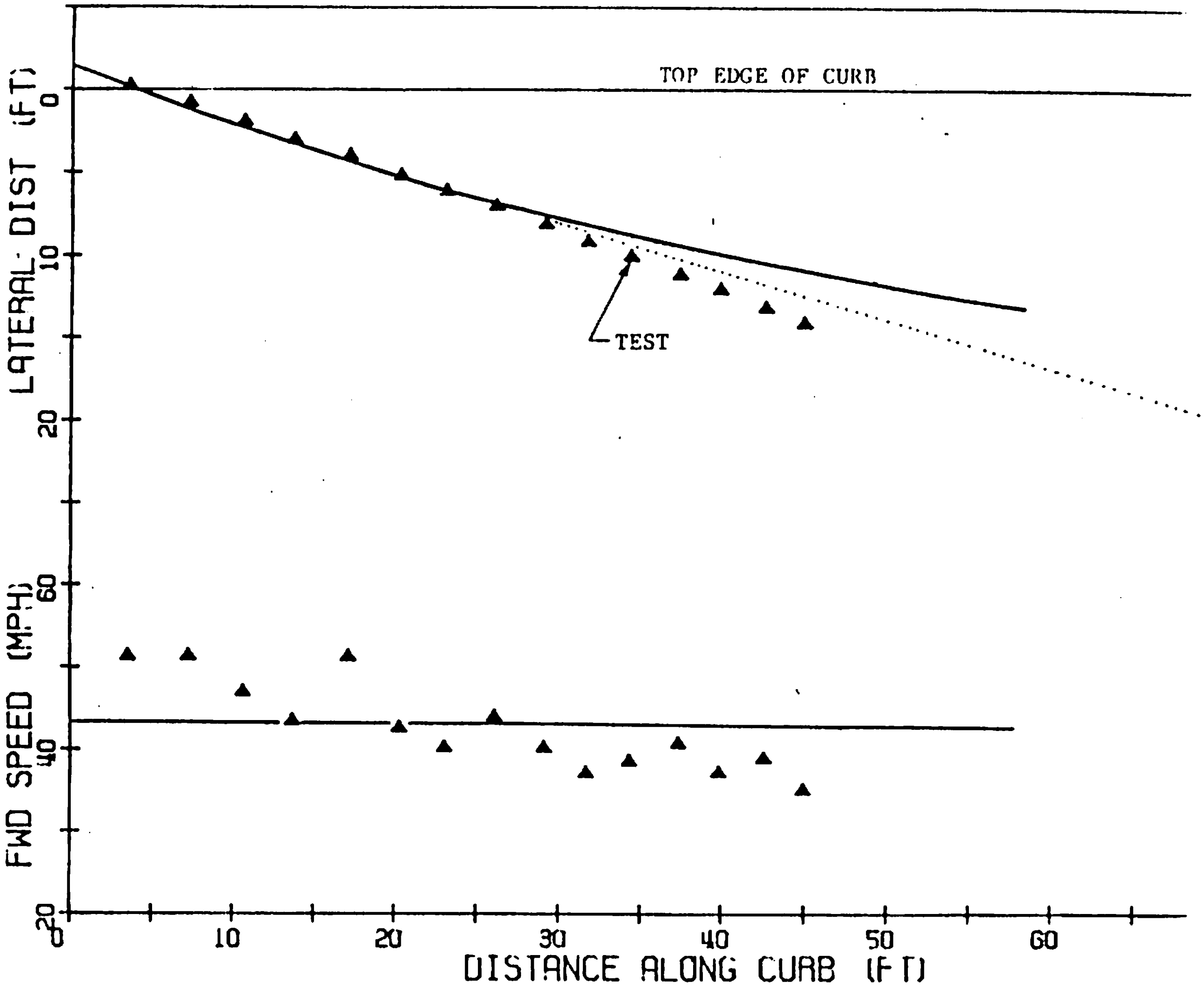
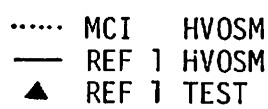


Figure 22. Test No. N-16 (Cont'd).



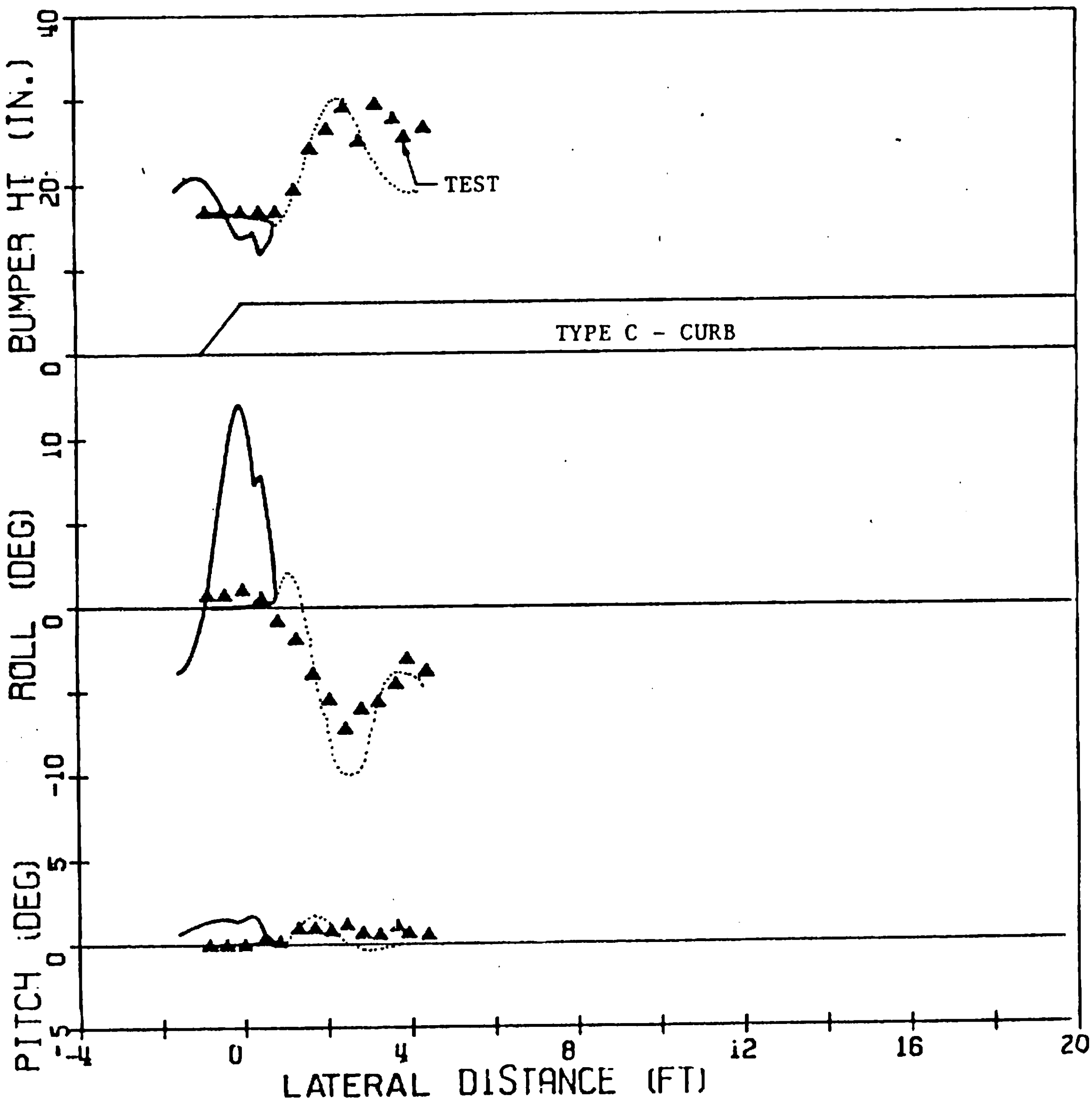


Figure 23. Test No. N-17.

66.5 MPH
5.1 DEG
Curb Type C

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

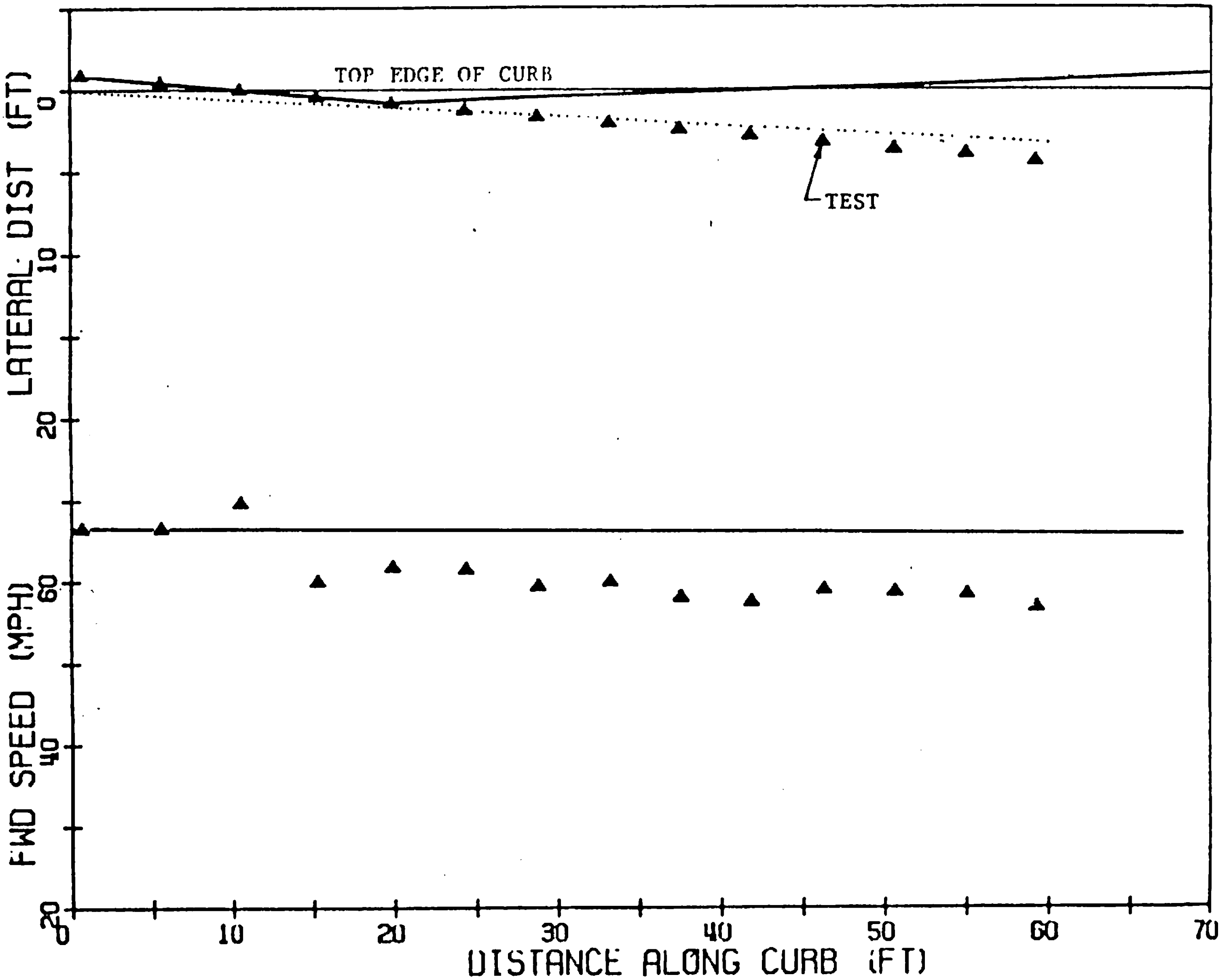


Figure 24. Test No. N-17 (Cont'd).

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

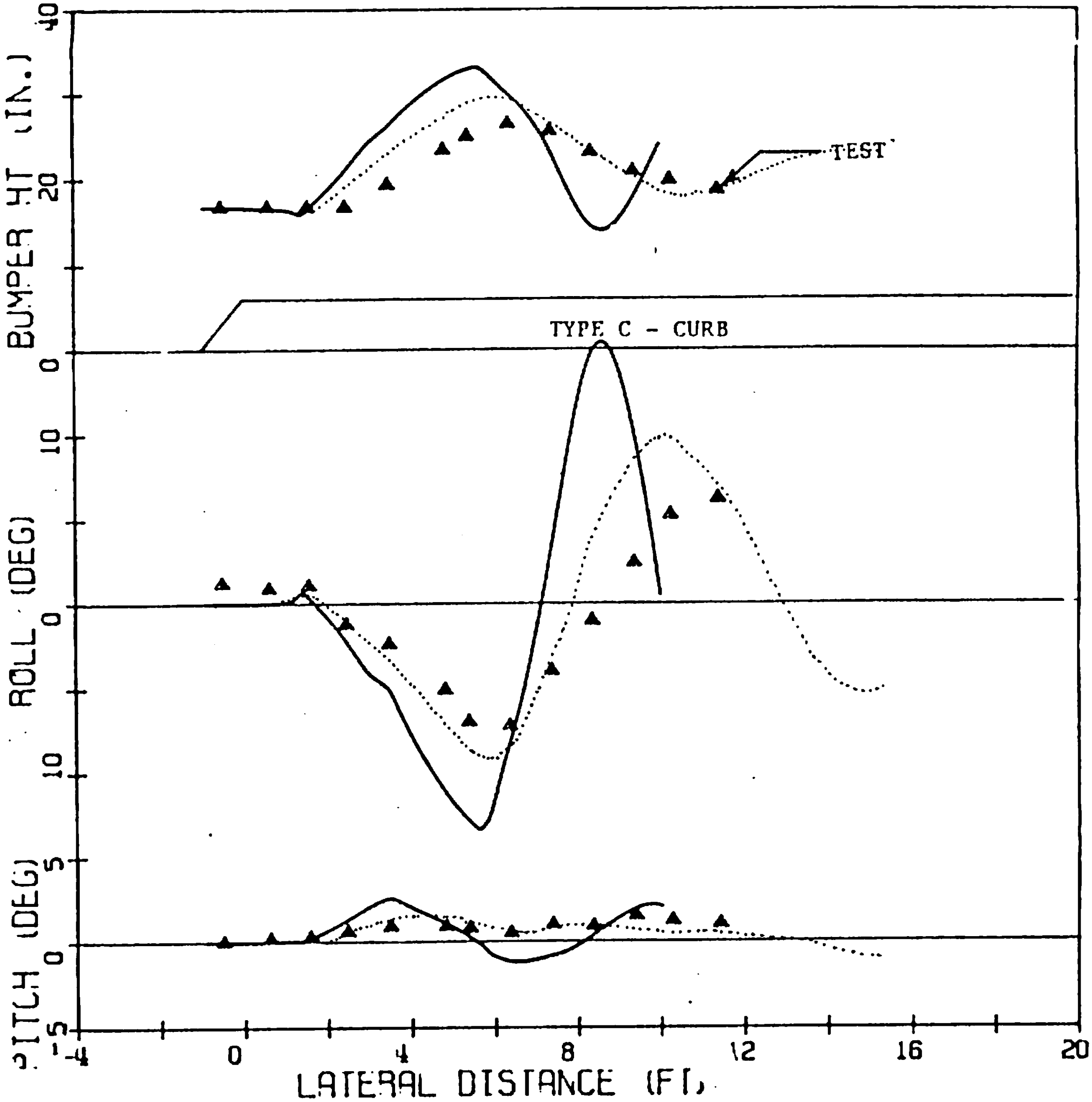


Figure 25. Test No. N-18.

62.2 MPH
12.3 DEG
Curb Type C

······ MCI HVOSM
—— REF 1 HVOSM
▲ REF 1 TEST

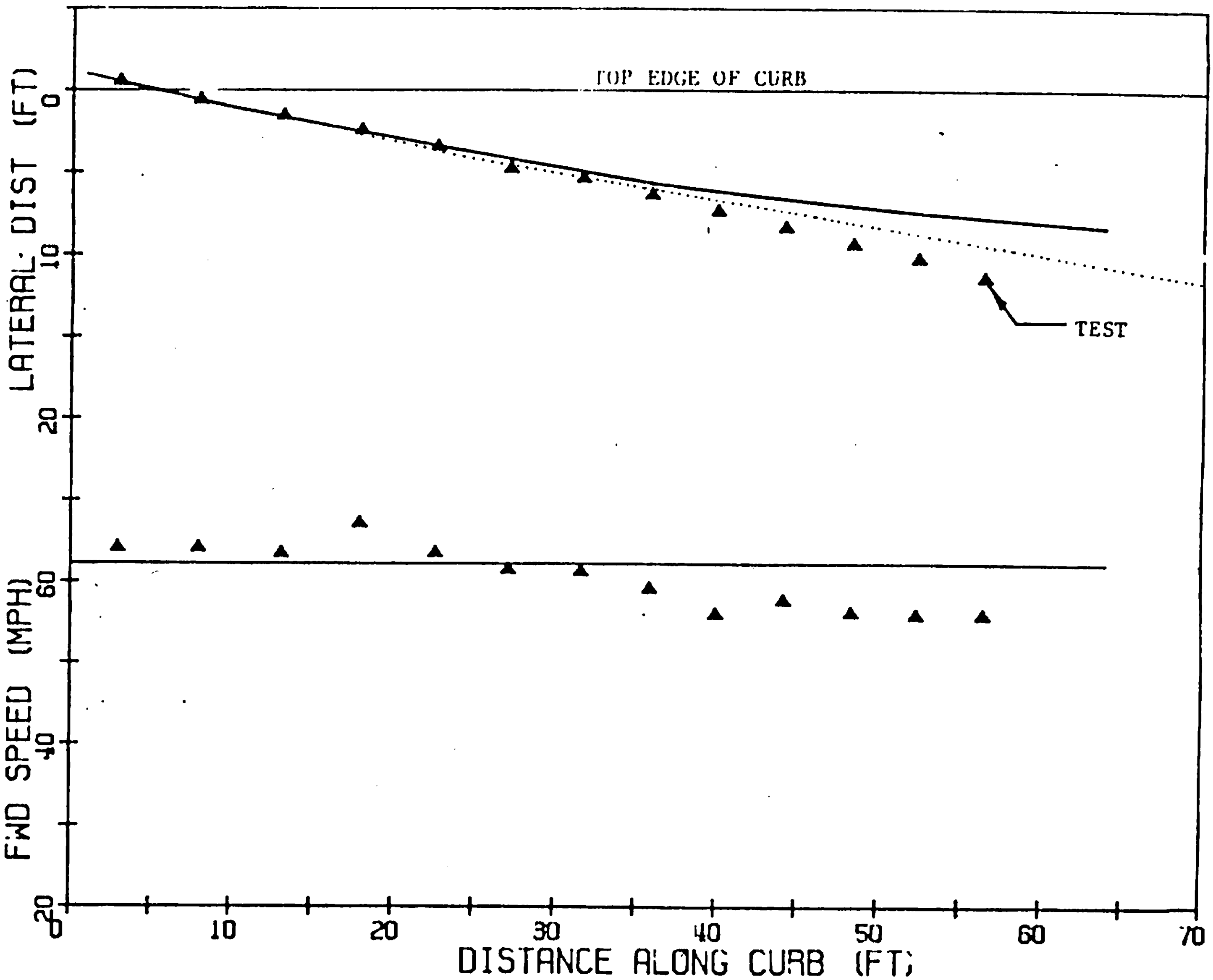


Figure 26. Test No. N-18 (Cont'd).

Parametric Studies

Sample comparisons of the reported results of parametric simulation studies in Reference 1, for the type X and type H curbs, with corresponding results obtained using the revised input parameters to define the vehicle and the steering system properties, revealed major differences in the extents of the maximum responses in the form of roll, pitch and bumper rise (i.e., the simulations performed in the present study had maximum values considerably smaller than those reported in Reference 1). The cited differences in response predictions, coupled with the neglect of sprung-mass contact forces which would be expected to occur as a result of front-bumper and undercarriage contact with the higher curbs raises serious doubts regarding the validity of conclusions in Reference 1 with respect to the type X curb and to some extent the type H curb.

4.0 REFERENCES

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(3) Ford Motor Company. "Final Report: Determination of Selected Vehicle Properties on a 1963 Ford Galaxie-4 dr. Sedan." Cornell Aeronautical Laboratories, Inc. Test Order No. E-7012, August 12, 1968.

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APPENDIX A

PARAMETER VALUES USED IN HVOSM SIMULATION

The reported simulation study has made use of the 1976 Highway-Vehicle-Object Simulation Model (HVOSM), Roadside-Design Version, which is documented in report no. FHWA-RD-76-162 (Ref. 9). Figure 27 is a copy of the card image of the program inputs used in the reported simulation study. In the following, the sources of the input parameters are defined.

Background

The authors of Reference 1 used an HVOSM "parameter study" vehicle definition "differing in weight, inertial properties, suspension properties and tire properties" from the test vehicle for their response comparisons and "validation" of the HVOSM results for prediction of curb impact responses (Ref. 1, p. 18). Note that this course of action violated the earlier finding of one of the authors that "it is extremely important that compatible vehicle characteristics are used for comparison purposes" (Ref. 2, p. 59).

The "test" vehicle used in Reference 1 for the full-scale tests was a 4200-lb. 1963 Ford Galaxie that had been previously used by Cornell Aeronautical Laboratory, Inc. (CAL) in the initial validation of the Single Vehicle Accident Simulation Model (e.g., Ref. 5, 6, 7). The sprung mass of the vehicle was modified by Texas A & M, and the authors of Reference 1 reported "a lack of information on . . . its mass and

```
 MCI REVISED INPUTS OF TEXAS A&M RUN [illegible],NCHRP 150,TYPE E CURB                      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
MCI REVISED DEFINITION OF TEST VEHICLE                                                      0 200
9.317   0.608   0.945   5028.   28678.  33029.  -192.   435.6                               0 201
54.55   64.45   61.2    60.5    -2.0    46.52                                               0 202
54.55   0.0     0.0     -64.45  0.0     0.0     10.3    12.20                               0 203
131.0   300.0   600.0   300.0   600.0   0.500   -3.0    5.0                                 0 204
194.0   300.0   600.0   300.0   600.0   0.500   -4.0    4.5                                 0 205
1.3     58.0    0.001   1.75    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                            14.69                                                       0 302
DRIVELINE,AERODYNAMICS,FRICTION                                                             0 400
0.0     0.30    0.10    1.0     1.0     1.0                                                 0 401
-105.   -105.   -105.   -105.                                                               1 401
-315.   -315.   -315.   -315.                                                               2 401
 TYPE E CURB                                                                                0 500
200.0   200.5   204.4   206.1   211.1           1.0                                         0 507
-1.00   -5.30   -6.0    -6.1                                                                0 508
-87.133 -44.667 -22.383 -1.150  0.0                                                         0 509
41.8 MPH, 18.7 DEG                                                                          0 600
0.0     0.0     18.7    0.0     0.0     0.0     0.0     0.0                                 0 601
0.0     130.0   -24.14  735.68  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 27. Card image.

inertial properties" (Ref. 1, p. 18). However, the "test vehicle" was measured extensively in the above referenced CAL research program wherein its properties, other than the modified sprung mass and the steering system dynamics, were measured and defined by the Ford Motor Company (Ref. 3) and the corresponding HVOSM inputs were documented by CAL.

The modifications of the vehicle reported in Reference 1 were as follows:

(1) Removal of the rear seat to install instrumentation.

(2) Replacement of the bench-type front seat with a bucket seat.

(3) Installation of a light-frame roll bar.

(4) Removal of the windshield and side glass and installation of wire mesh.

Modifications were made in the partially defined "parameter study" vehicle properties of Reference 1 for the simulation study reported herein. The modifications were aimed at achieving an accurate representation of the test vehicle to the greatest extent possible within the limitations of the available information. Clearly, a realistic assessment of the validity of HVOSM response predictions for curb impacts requires that comparisons with test results be based on simulation runs using measured properties of the test vehicle.

In the following paragraphs, the basis for various input parameters is discussed. Inputs not included in the discussion are considered to be self-explanatory.

Cards 201, 202

In Figure B-2 of Reference 1, the "vehicle C.G." of the test vehicle is shown to be 54.55 inches aft of the front wheel centerline. Note that Figure B-2 and the related text do not distinguish between the sprung mass C.G. and the total vehicle C.G. However, in view of the described vehicle modifications, the previous location of the sprung mass C.G. (i.e., 54.517 inches aft of the front wheel centerline), and the indicated C.G. elevation in Figure B-2 (24.138 inches) it is assumed that the "vehicle C.G." in Figure B-2 is actually the sprung mass center of gravity.

The moments of inertia for the test vehicle that are listed in Figure A-7 of Reference 1 were based on relationships attributed to Rasmussen of General Motors. However, it should be noted that the values for the pitch and yaw moments of inertia were calculated with Rasmussen's relationships for the total vehicle whereas the HVOSM inputs should be for the sprung mass only:

$$I_{XS} = [0.16\ (4200) - 265]\ 12 = 4884 \text{ lb sec}^2 \text{ in}$$

$$I_{YT} = [1.13\ (4200) - 2020]\ 12 = 32712 \text{ lb sec}^2 \text{ in}$$

$$I_{ZT} = [1.26\ (4200) - 1750]\ 12 = 42504 \text{ lb sec}^2 \text{ in}$$

A correct application of Rasmussen's relationships for the sprung mass yields the following:

$$I_{ZS} = (1.05\ W_t - 1470)\ 12 = 35280 \text{ lb sec}^2 \text{ in}$$

$$I_{YU}^{CGT} = [\frac{234.9}{32.2}\ (21.66) + \frac{365.1}{32.2}\ (29.85)]\ 12$$

$$= 5957.6 \text{ lb sec}^2 \text{ in}$$

$$I_{YS}^{CGT} = 32712 - 5957.6 = 26754.4 \text{ lb sec}^2 \text{ in}$$

$$I_{YS}^{CGS} = 26754.4 + \frac{4200}{386.4}(2.98)^2$$

$$= 26851 \text{ lb sec}^2 \text{ in}$$

In recognition of the facts that (1) the radii of gyration would not have been substantially changed from those reported in Reference 7 and (2) the Rasmussen values are approximate, "typical" values, the radii of gyration were assumed to be best approximated by averaging the values from the Rasmussen relationships and those from Reference 7. On this basis, the following values were obtained for the moments of inertia:

$$I_X = 5028. \text{ lb sec}^2 \text{ in}$$

$$I_Y = 28678. \text{ lb sec}^2 \text{ in}$$

$$I_Z = 33029. \text{ lb sec}^2 \text{ in}$$

The roll-yaw product of inertia was assumed to be approximately equal to the value in Reference 7 (i.e., $I_{XZ} = -192$ lb sec^2 in).

Since there were no modifications of the unsprung masses, the parameter values from Reference 7 were retained.

$$M_S = 9.317 \text{ lb sec}^2/\text{in}$$

$$M_{UF} = 0.608 \text{ lb sec}^2/\text{in}$$

$$M_{UR} = 0.945 \text{ lb sec}^2/\text{in}$$

$$I_R = 435.6 \text{ lb sec}^2/\text{in}$$ lb sec² in X

On the basis of the indicated interpretation of Figure B-2, the following dimensional inputs were obtained from that figure:

A = 54.55 inches

B = 64.45 inches

119.00 inches

Other dimensional inputs for card 201 were assumed to be unchanged from those in Reference 7:

T_F = 61.2 inches

T_R = 60.5 inches

T_S = 46.52 inches

ρ = -2.0 inches

Cards 204, 205

A number of inconsistencies were found between the values of parameters apparently used in the simulation study of Reference 1 and the corresponding definitions.

(1) Deflection Limiting Stops

McHenry and DeLeys (Ref. 14) concluded that the symmetrical and elastic deflection-limiting stops used in their previous report (Ref. 7) were a significant source of discrepancies between predicted and measured vehicle motions. Therefore, they revised the HVOSM program, as a part of the research reported in Ref. 14, to permit unsymmetrical placement of the jounce and rebound bumpers with respect to the design positions of the wheels and to provide for an adjustable amount of energy dissipation in the suspension bumpers.

In the incomplete listing of input values that is presented in Reference 1, inputs for both symmetrical-elastic and unsymmetrical-energy-dissipating suspension bumpers are included. Thus, it is not clear what was actually used in the simulation study. Note that a card image and/or an identification of the version of HVOSM would have been most helpful.

(2) Suspension Bumper Force Expressions

Suspension bumper force expressions in the version of HVOSM currently available from FHWA, which has been utilized in the present research, contain an important modification of the manner in which the coefficients of the cubic terms within the suspension bumper force expressions are applied. Segal (Ref. 9) revised the equations as follows:

In V-7 version, ref. 14, p. 62:

$$K_C\ (\delta - \Omega_C) + K_C\ K_C^{'}\ (\delta - \Omega_C)^3$$

In HVOSM-1976 version, ref. 9, p. 329:

$$K_C\ (\delta - \Omega_C) + K_C^{'}\ (\delta - \Omega_C)^3$$

The present simulation study required an alteration of the values of AKFCP, AKFEP, AKRCP and AKREP from 2. lb/in^3 to 300 lb/in^3 to retain the original load-deflection characteristics of Reference 7.

Card 207

The values from Reference 7 were retained.

Card 208 (Steering System)

The steering system properties used as input for the HVOSM simulations of Reference 1 were not specified in the report. A review of the references cited in Reference 1 revealed that the probable parameter values used were the same as those estimated in the early developmental stages of HVOSM (i.e., card 17 of HVOSM version defined in Ref. 7). Apparently, no direct measurements of the steering system properties have been made or documented on the 1963 Ford Galaxie.

The high speed and/or large encroachment angle simulation runs with the revised vehicle definition correlated well with the full-scale test results using the original estimated values for the steering system properties. Low speed and/or shallow angle simulation runs did not correlate as well with the full-scale tests. In many instances it was found that the simulation run predicted a redirection that did not occur in the full-scale tests.

Large steer angles accompanied the redirection predictions in the simulation runs as the result of front wheel contacts with the curb in the low speed, shallow angle runs. The steering system responses to the curb contacts were not measured in the full-scale tests.

Exploratory simulation runs were performed to test the sensitivity of the steering system response amplitude to the simulated coulomb friction torque (CPSP) and the corresponding effects on vehicle redirection. A range from 500 lb-in to 5000 lb-in was included. A comparison of the simulated vehicle responses and the full-scale test results led to the conclusion that a value of 5000 lb-in for CPSP produced the best correlation of redirection for low-speed, shallow angle contacts with curbs.

The larger value of steering system coulomb friction torque did not significantly affect the generally good correlation with the higher speed and/or angle curb contacts.

Card 209 (Camber and Half-~~Touch~~ Changes)

It was found in Young's report (Ref. 4) that estimated values, as opposed to the Ford Motor Co. measurements, for the camber change were used in the simulation study of Reference 1. Young references VJ-2251-V-3 by McHenry and DeLeys (Ref. 7) for the camber data but selects the estimated rather than the measured data set. The data set entitled "Best Estimate" on pp. 71-72 of Reference 7 should have been used. It represents data derived directly from Ford Motor Co. measurements (Ref. 3).

Cards 210, 211
Suspension Anti-Pitch Coefficients,
Front and Rear

The DeLeys report (Ref. 8) was used as the source for these values.

Cards 301, 302
Tire Characteristics

For the full-scale tests it was reported that Uniroyal G78-14 bias-belted, polyester-fiberglass tires mounted on six-inch rims were used. The source used for input parameters for these tires was Pizralli's report (Ref. 15).

Values for SIGT and AMU from DeLeys' report (Ref. 8) were considered to be representative of the properties of tires in the curb impact test situation.

Card 400
Vehicle Control Inputs

In Reference 1, it is stated that HVOSM cannot accommodate aerodynamic forces and inertial drag of the engine, drive shaft and so forth.

The effects of such motion resistance can, of course, be approximated by means of the application of low values of braking torque at the front and rear wheels.

Cards 507-509
Curb Definitions

Within the reported research effort of Reference 1, the curb input routine was modified to include up to 6 curb faces. The corresponding inputs were retained in the present runs.

Without explanation or discussion, the researchers of Reference 1 varied the curb friction coefficient from 0.5 to 0.8 for the different curbs. Within the presently reported research effort, variations of the curb face friction coefficient were found to produce insignificant effects on the vehicle behavior. Therefore, a friction coefficient equal to the nominal tire-ground friction coefficient was used in all runs.

It should be noted that the present version of HVOSM, as documented in Reference 9, calls for input of a friction coefficient multiplier AMUC of the nominal-tire friction coefficient. Therefore, the value of AMUC was entered as 1.0. In earlier versions of HVOSM the value for the friction coefficient was input directly.

APPENDIX B

HVOSM POST-PROCESSING PROGRAM

As a part of the performance of the reported HVOSM curb-impact studies, it was necessary to compare some aspects of predicted vehicle responses, which are not a part of the normal HVOSM outputs, with results of full-scale tests and earlier HVOSM runs presented in graphical form in Reference 1 (pp. 44-61, pp. 67-88).

The variables used for comparison purposes in Reference 1 were:

bumper rise (in)	vs.	lateral distance (ft)
vehicle roll (in)	vs.	lateral distance (ft)
vehicle pitch (in)	vs.	lateral distance (ft)
vehicle speed (mph)	vs.	distance along curb (ft)
lateral distance (ft)	vs.	distance along curb (ft)

Reference 1 contains no documentation of the specific reference points used for bumper height, lateral distance from the curb and distance along the curb. Therefore, it was necessary to make the following selections:

Bumper Height: The only reference to the location of the point on the bumper for which the elevation was calculated is "the mid-point of the right front corner (16.75 in from ground level)" (Ref. 1, p. 9). The coordinates in the vehicle-fixed frame of reference were assumed to be:

BUMP X = 81.517
BUMP Y = 39.500
BUMP Z = 7.390

The indicated coordinate corresponds to a sprung-mass CG height of -24.14 inches.

Lateral Distance: The lateral distance of the point of interest was measured using the space-fixed Y'-coordinate of the top point of the curb as the zero reference.

	Zero Reference (Y' Direction)
TYPE C CURB	219.55 inches
TYPE E CURB	206.10 inches
TYPE H CURB	220.00 inches
TYPE X CURB	207.70 inches

Distance Along Curb: Two lateral distance reference points are utilized, one which represents the front edge of the curb and the other representing the top edge of the curb. The distance along the curb was measured with the zero reference being the X-coordinate of the vehicle point of interest when its space-fixed Y-coordinate first reached the Y-reference point.

For comparisons with the full-scale tests the Y-reference was the same as that used for lateral distance calculation. For the simulation studies (i.e., computer runs not compared with experiments), the Y-reference was the front edge of the curb. This had a value of 200.00 inches for all runs. The indicated use of different reference points is in accordance with the contents of Reference 1.

The user input to the post-processing program is:

(1) Punched card input as Fortran Unit 1 containing the following information:

		Variable	Definition
Col.	1-10 11-20 21-30	BUMPX BUMPY BUMPZ	Coordinates of the point of interest in vehicle-fixed frame of reference, inches
	31-40	YREF	Y-coordinate in space-fixed frame of reference of the top of curb, inches
	41-50	YREF2	Y-coordinate in space-fixed frame of reference of the edge of the curb, inches
	51-60	INTVEL	Initial velocity of the vehicle, MPH
	61-70	CURBZ	Height of curb (enter as positive), inches

(2) Time history data read from Fortran Unit 9.

The existing versions of HVOSM contain subroutine PLOTTP (IPLT) which creates a time history tape for post-processing graphics displays. The information on this tape is ideal for the input requirements of the present post-processing program.[1]

For the Post-Processing Program, the following parameters were read from the time history tape:

First Static Record

Words	Type	Symbol	Purpose
1-36	A	TITLE	Descriptive title, same as card 100 on HVOSM input data deck.
37-39	A	DAY	Date of HVOSM run same that appears on HVOSM output
40-46	F F I F	ADIST BDIST ISUS RW(4)	Read in but not used

[1]The reader is referred to Ref. (11), (12), and (13) for more detailed information.

Dynamic Records

Words	Type	Symbol	Purpose
1	F	T	Simulation time (sec)
2	F	X	Displacement of chassis
3	F	Y	c.g. from fixed space origin (inches)
4	F	Z	
5	F	PHI	Roll, pitch, yaw, Euler angle
6	F	THETA	rotations of chassis in fixed space
7	F	PSI	(radians)
8-39	F		Read in but not used

Final Record

Words	Type	Symbol	Purpose
1	F	VARN(1)	Floating point value of -9999.00

Dynamic records were read into the array VARN(39). An equivalence statement was used to equate the values in the array with the constants used in calculation. A simple check for

If (VARN(1) = -9999.00)

signals end of data.

The transformation (A) matrix was utilized for transforming the coordinates in the vehicle-fixed frame of reference to the coordinates in the space-fixed reference system. The procedure for this transformation is as follows:

$$\begin{vmatrix} XPI \\ YPI \\ ZPI \end{vmatrix} = \| A \| \cdot \begin{vmatrix} BUMPX \\ BUMPY \\ BUMPZ \end{vmatrix} + \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}$$

where: (X,Y,Z) = coordinates of vehicle C.G. in space-fixed frame of reference

(BUMPX, BUMPY, BUMPZ) = coordinates of the point of interest in vehicle-fixed frame of reference

(A) = Transformation matrix

to give: (XPI, YPI, ZPI) = coordinates of the point of interest in space-fixed frame of reference.

Velocity time-history information is not contained on the graphics tape, so it was calculated using:

$$\Delta S = \sqrt{(XPI)(I) - XPI(I-1))^2 + (YPI(I) - YPI(I-1))^2 + (ZPI(I) - ZPI(I-1))^2}$$

$$VEL(I) = \frac{\Delta S}{(T(I) - T(I-1))} \quad (.056818)$$

The user must input an initial value for the velocity since the preceding calculation procedure cannot be applied at t = 0.0.

```
C     MCI TRANSFORMATION PROGRAM FOR COMPARING HVOSM CURB IMPACT RUNS
C
C
C      MCHENRY CONSULTANTS,INC.
C      P.O. BOX 921
C      CARY, NORTH CAROLINA  27511
C       PROGRAMMER=B.MCHENRY          DATE=AUGUST 15,1980
C
C
C*****DESCRIPTION
C
C     CARD1 - BUMPX,BUMPY,BUMPZ,YREF,YREF2,INTVEL,CURBZ
C             CARD INPUT IN FIELDS OF 10
C
C
C
      DIMENSION VARN(23),WCON(13),XPI(200),YPI(200),ZPI(200),TR(200),
     1          YLAT(200),ROLL(200),PITCH(200),DISX(200),VELFWD(200),
     2          AMTX(3,3),BUMHT(200),YLAT2(200),BUMHT2(200),
     3          CGHT(200),DISX2(200)
      EQUIVALENCE (VARN(1),T),(VARN(2),X),(VARN(3),Y),(VARN(4),Z),
     1            (VARN(5),PHI),(VARN(6),THETA),(VARN(7),PSI)
      REAL INTVEL,INCR,TITLE(36),DAY(3),RW(4)
      RAD=57.29577951
      NUMPTS=0
      XREF=0.0
      XREF2=0.0
C READ IN USER INPUT CARDS FROM FT01F001
      READ(1,1) BUMPX,BUMPY,BUMPZ,YREF,YREF2,INTVEL,CURBZ
1     FORMAT(7F10.3)
C READ IN 1ST STATIC RECORD FROM TAPE FT09F001
      READ(9) TITLE,DAY,ADIST,BDIST,ISUS,RW
      WRITE(3,3006) (TITLE(K),K=1,20),DAY
3006  FORMAT(1H1,20A4,15X,12HDATE OF RUN:,3A4)
      WRITE(3,3021)
3021  FORMAT(1H0,42H  LIST OF USER INPUTS READ FROM FT01F001      /
     A        1H0,4X,5HBUMPX,5X,5HBUMPY,6X,5HBUMPZ,5X,
     14HYREF,6X,4HYREF,1H2,6X,6HINTVEL,5X,5HCURBZ)
      WRITE(3,3020) BUMPX,BUMPY,BUMPZ,YREF,YREF2,INTVEL,CURBZ
3020  FORMAT(1H ,7(F10.3))
      DO 6 I=1,200
C READ DYNAMIC PARAMETERS FROM TAPE FT09F001
      READ(9,END=998) VARN,WCON
C  CHECK IF FINAL STATIC RECORD READ FROM FT01F001
C
      IF(T.EQ.-9999.0) GO TO 998
C
C  SET TIME
      TR(I)=T
C CALCULATE BUMPER COORDINATES IN SPACE FIXED FRAME OF REFERENCE
C
      AMTX(1,1) = COS(THETA)* COS(PSI)
      AMTX(2,1) = COS(THETA) * SIN(PSI)
      AMTX(3,1)= -SIN(THETA)
      AMTX(1,2) = -COS(PHI) * SIN(PHI) * SIN(THETA) * COS(PSI)
      AMTX(2,2) = COS(PHI) * COS(PSI) + SIN(PHI) * SIN(THETA)
     1            * SIN(PSI)
      AMTX(3,2) = COS(THETA) * SIN(PHI)
      AMTX(1,3) = SIN(PHI) * SIN(PSI) + COS(PHI) * SIN(THETA)
     1            * COS(PSI)
      AMTX(2,3) = -COS(PSI) * SIN(PHI) + COS(PHI) * SIN(THETA)
     1            * SIN(PSI)
      AMTX(3,3) = COS(THETA) * COS(PHI)
C
      XPI(I)=X+AMTX(1,1)*BUMPX+AMTX(1,2)*BUMPY+AMTX(1,3)*BUMPZ
      YPI(I)=Y+ AMTX(2,1)*BUMPX+AMTX(2,2)*BUMPY+AMTX(2,3)*BUMPZ
      ZPI(I)=Z+AMTX(3,1)*BUMPX+AMTX(3,2)*BUMPY+AMTX(3,3)*BUMPZ
C CALCULATE VELOCITY
      IF(I.EQ.1) GO TO 8
      DELS=SQRT((XPI(I)-XPI(I-1))**2+(YPI(I)-YPI(I-1))**2+
     1          (ZPI(I)-ZPI(I-1))**2)
      VELFPS=DELS/(TR(I)-TR(I-1))
      VELFWD(I)=(VELFPS*30.0)/(44.0*12.0)
      GO TO 10
8     VELFWD(I)=INTVEL
10    CONTINUE
```

Figure 28

MCI HVOSM Post-Processing Program Listing

```
C FILL ARRAYS
      NUMPTS=NUMPTS+1
      BUMHT(I)=ZPI(I)
      BUMHT2(I)=ABS(ZPI(I))-CURBZ
      CGHT(I)=ABS(Z)-CURBZ
      YLAT(I)=(YPI(I)-YREF)/(12.0)
      YLAT2(I)=(Y-YREF2)/12.0
      ROLL(I)=PHI*RAD
      PITCH(I)=THETA*RAD
C  TEST FOR YLAT=0.0, TO SET UP XREF
      IF(XREF.NE.0.0) GO TO 12
      IF(YLAT(I).GE.0.0) GO TO 4
      DISX(I)=0.0
      XREF=0.0
      GO TO 60
4     XREF=XPI(I)
      DISX(I)=0.0
      GO TO 60
12    DISX(I)=(XPI(I)-XREF)/12.0
60    CONTINUE
C
C  TEST FOR YLAT2=0  TO SET UP XREF2
C
      IF(XREF2.NE.0.0) GO TO 14
      IF(YPI(I).GE.YREF2) GO TO 15
      DISX2(I)=0.0
      XREF2=0.0
      GO TO 61
15    XREF2=X
      DISX2(I)=0.0
      GO TO 61
14    DISX2(I)=(X-XREF2)/12.0
61    CONTINUE
6     CONTINUE
C
C PRINT OUTPUT
999    CONTINUE
998   CONTINUE
      DO 1001 J=1,NUMPTS
C HEADERS WRITTEN FOR 1ST,55TH,101TH,156TH.
      IF(J.EQ.1) GO TO 1002
      IF(J.EQ.55) GO TO 1002
      IF(J.EQ.101) GO TO 1002
      IF(J.EQ.156) GO TO 1002
      GO TO 1003
1002  WRITE(3,1007)(TITLE(K),K=1,20),DAY
1007  FORMAT(1H1,20A4,15X,3A4)
      WRITE(3,1004)
1004  FORMAT(
```

Figure 29.
MCI HVOSM Post-Processing Program Listing (cont.)

```
     D1H ,100X,  /
     E1H ,69X,8HDISTANCE  /
     F1H ,34H                LATERAL        BUMPER
     G37X,26HALONG     LATERAL      FWD      /
     Z1H
     H60H  TIME       DISTANCE      HEIGHT         ROLL          PITCH
     I50H             CURB      DISTANCE     SPEED               /
     X1H
     J60H  (SEC)        (FT)          (IN)          (DEG)          (DEG)
     K12X,30H(FT)       (FT)       (MPH)        /
     L1H ,100X,10H             /  )
C
1003  WRITE(3,1005) TR(J),YLAT(J), BUMHT(J),ROLL(J),PITCH(J),DISX(J),
     1               YLAT(J),VELFWD(J)
1005  FORMAT(' ',F7.4,4(3X,F10.2),5X,3(2X,F10.2))
C
1001  CONTINUE
      DO 1020 J=1,NUMPTS
      IF(J.EQ.1) GO TO 1021
      IF(J.EQ.55) GO TO 1021
      IF(J.EQ.101) GO TO 1021
      IF(J.EQ.156) GO TO 1021
      GO TO 1024
1021  WRITE(3,1022) (TITLE(K),K=1,20),DAY
1022  FORMAT(1H1,20A4,15X,3A4)
      WRITE(3,1023)
1023  FORMAT(
     A1H0,12X,22HBUMP LATERAL    BUMPER,8X,2HCG,13X,7HCG DIST,
     B4X,20HCG LATERAL   VEHICLE,5X,7HVEHICLE /
     C1H ,6H  TIME,9X,8HDISTANCE,6X,3HHGT,10X,3HHGT,10X,
     D10HALONG CURB,4X,17HDISTANCE     ROLL,8X,5HPITCH /
     E1H ,7H  (SEC),10X,4H(FT),8X,4H(IN),8X,4H(IN),14X,
     F4H(FT),8X,4H(FT),8X,5H(DEG),7X,5H(DEG)  /)
1024  WRITE(3,1025) TR(J),YLAT(J),BUMHT2(J),CGHT(J),DISX2(J),
     1              YLAT2(J),ROLL(J),PITCH(J)
1025  FORMAT(1H ,F7.4,3(3X,F10.2),5X,4(2X,F10.2))
1020  CONTINUE
      END
//*
```

Figure 30.
MCI HVOSM Post-Processing Program Listing (cont.)

; OF TEXAS A&M RUN N-7,NCHRP 150,TYPE E CURB

JTS READ FROM FT01F001

'	BUMPZ	YREF	YREF2	INTVEL	CURBZ
)0	7.390	200.100	200.000	63.600	6.000

Figure 31.
ımple Outputs from MCI HVOSM Post-Processing Program

[illegible]	[illegible]	15.06	19.32	14.93	-1.35	-2.48	0.99
0.1900	2.89	15.44	19.41	15.38	-1.25	-2.72	1.08
0.1950	2.98	15.82	19.51	15.83	-1.16	-2.96	1.16
0.2000	3.07	16.19	19.60	16.28	-1.06	-3.19	1.24
0.2050	3.17	16.56	19.70	16.73	-0.97	-3.42	1.32
0.2100	3.26	16.92	19.80	17.18	-0.88	-3.65	1.40
0.2150	3.35	17.29	19.90	17.63	-0.79	-3.88	1.47
0.2200	3.45	17.65	20.00	18.08	-0.70	-4.11	1.54
0.2250	3.54	18.00	20.10	18.53	-0.61	-4.35	1.60
0.2300	3.63	18.35	20.21	18.97	-0.51	-4.59	1.65
0.2350	3.72	18.70	20.33	19.42	-0.42	-4.84	1.69
0.2400	3.82	19.05	20.45	19.87	-0.33	-5.12	1.71
0.2450	3.91	19.40	20.59	20.32	-0.24	-5.42	1.71
0.2500	4.00	19.76	20.74	20.77	-0.15	-5.73	1.71
0.2550	4.09	20.11	20.89	21.22	-0.06	[illegible]	1.69
0.2600	4.18	20.45	21.04	21.67	0.02	[illegible]	1.67
0.2650	4.28	20.79	21.20	22.12	0.11	[illegible]	1.64

am (cont.)

MCI REVISED INPUTS OF TEXAS A&M RUN N-7, NCHRP 150, TYPE E CURB 09/09/80

TIME (SEC)	LATERAL DISTANCE (FT)	BUMPER HEIGHT (IN)	ROLL (DEG)	PITCH (DEG)	DISTANCE ALONG CURB (FT)	LATERAL DISTANCE (FT)	FWD SPEED (MPH)
0.0	-0.81	-16.75	0.0	0.0	0.0	-0.81	63.60
0.0050	-0.71	-16.75	0.00	-0.00	0.0	-0.71	63.59
0.0100	-0.61	-16.75	0.00	-0.00	0.0	-0.61	63.57
0.0150	-0.51	-16.75	0.00	-0.00	0.0	-0.51	63.55
0.0200	-0.41	-16.74	0.00	-0.00	0.0	-0.41	63.53
0.0250	-0.31	-16.74	0.00	-0.01	0.0	-0.31	63.51
0.0300	-0.20	-16.73	0.00	-0.01	0.0	-0.20	63.49
0.0350	-0.10	-16.73	0.00	-0.01	0.0	-0.10	63.47
0.0400	-0.00	-16.72	0.00	-0.01	0.0	-0.00	63.45
0.0450	0.10	-16.72	0.00	-0.02	0.0	0.10	63.43
0.0500	0.20	-16.71	0.00	-0.02	0.45	0.20	63.42
0.0550	0.30	-16.70	0.00	-0.03	0.91	0.30	63.40
0.0600	0.40	-16.69	0.00	-0.03	1.36	0.40	63.38
0.0650	0.51	-16.68	0.00	-0.03	1.81	0.51	63.36
0.0700	0.61	-16.68	0.00	-0.04	2.27	0.61	63.34
0.0750	0.71	-16.66	0.01	-0.04	2.72	0.71	63.32
0.0800	0.81	-16.64	0.03	-0.05	3.17	0.81	63.29
0.0850	0.91	-16.61	0.07	-0.05	3.63	0.91	63.25
0.0900	1.00	-16.56	0.12	-0.06	4.08	1.00	63.21
0.0950	1.10	-16.50	0.19	-0.07	4.53	1.10	63.18
0.1000	1.19	-16.44	0.26	-0.07	4.99	1.19	63.14
0.1050	1.28	-16.39	0.32	-0.08	5.44	1.28	63.11
0.1100	1.38	-16.38	0.36	-0.08	5.90	1.38	63.10
0.1150	1.47	-16.50	0.31	-0.04	6.35	1.47	63.12
0.1200	1.56	-16.74	0.17	0.01	6.80	1.56	63.18
0.1250	1.66	-17.04	-0.01	0.08	7.25	1.66	63.20
0.1300	1.75	-17.36	-0.19	0.16	7.71	1.75	63.20
0.1350	1.85	-17.68	-0.39	0.23	8.16	1.85	63.18
0.1400	1.94	-18.00	-0.58	0.31	8.61	1.94	63.17
0.1450	2.04	-18.32	-0.77	0.38	9.06	2.04	63.15
0.1500	2.13	-18.64	-0.97	0.45	9.52	2.13	63.13
0.1550	2.23	-18.96	-1.17	0.53	9.97	2.23	63.11
0.1600	2.32	-19.29	-1.37	0.60	10.42	2.32	63.10
0.1650	2.42	-19.62	-1.57	0.67	10.87	2.42	63.08
0.1700	2.51	-19.96	-1.79	0.75	11.33	2.51	63.07
0.1750	2.60	-20.31	-2.01	0.83	11.78	2.60	63.06
0.1800	2.70	-20.68	-2.24	0.91	12.23	2.70	63.07
0.1850	2.79	-21.06	-2.48	0.99	12.68	2.79	63.05
0.1900	2.89	-21.44	-2.72	1.08	13.13	2.89	63.03
0.1950	2.98	-21.82	-2.96	1.16	13.58	2.98	62.99
0.2000	3.07	-22.19	-3.19	1.24	14.03	3.07	62.93
0.2050	3.17	-22.56	-3.42	1.32	14.48	3.17	62.88
0.2100	3.26	-22.92	-3.65	1.40	14.94	3.26	62.84
0.2150	3.35	-23.29	-3.88	1.47	15.39	3.35	62.82
0.2200	3.45	-23.65	-4.11	1.54	15.84	3.45	62.79
0.2250	3.54	-24.00	-4.35	1.60	16.29	3.54	62.76
0.2300	3.63	-24.35	-4.59	1.65	16.73	3.63	62.74
0.2350	3.72	-24.70	-4.84	1.69	17.18	3.72	62.70
0.2400	3.82	-25.05	-5.12	1.71	17.63	3.82	62.66
0.2450	3.91	-25.40	-5.42	1.71	18.08	3.91	62.62
0.2500	4.00	-25.76	-5.73	1.71	18.53	4.00	62.60
0.2550	4.09	-26.11	-6.05	1.69	18.98	4.09	62.56
0.2600	4.18	-26.45	-6.36	1.67	19.43	4.18	62.53

Figure 32. Sample Outputs from HVOSM Post-Processing Program (cont.)