V. ASSESSMENT OF VEHICLE-TO-CURB IMPACTS USING FEM

5.1 Introduction

Vehicle impact with roadside curbs can often result in the driver losing control of the vehicle. There are many factors that influence vehicle behavior during such an event, such as abrupt steering caused by the interaction of the front wheels with the curb, loss of contact between the tires and ground, excessive vehicle accelerations and excessive roll, pitch and yaw rates of the vehicle during impact. Each of these factors may lead to loss of control of the vehicle, however, total loss of control is unlikely except in extreme cases. A more important issue may be the effects that these factors precipitate when curbs are placed in combination with roadside barriers (e.g., guardrail, crash cushions, breakaway poles, etc). For example, the trajectory of a vehicle after crossing a curb may be insignificant regarding the potential for losing control of the vehicle, but even a slight trajectory may be sufficient to cause the vehicle to impact a roadside safety device at a point higher or lower than normal, which may lead to override or underride of roadside barriers or may adversely affect the breakaway mechanism of various breakaway roadside hardware devices.

The kinematic behavior of a vehicle traversing a roadside curb is the primary focus of this chapter. The modified NCAC finite element model of the C2500 pickup truck (see chapter 4) will be used to investigate the vehicle's response when crossing a number of different curb types at various impact conditions. The information collected in this phase of the study will serve two purposes: 1) to quantify the effects that vehicle impact with curbs have on the stability of the vehicle and 2) to provide information regarding the trajectory and path of the vehicle after impact with curbs. The later will be used to establish critical placement of curbing with respect to the position of roadside barriers that are likely to result in success or failure of the barrier system. These critical offset distances of curb-to-barrier will be further investigated in the following chapter titled 'Vehicle Impact with Curb-and-Guardrail Systems'.

5.2 Parametric Study

The case of a vehicle impacting a curb in a tracking manner will be investigated using LS-DYNA. In the initial stages of this research it was envisioned that the response of a vehicle crossing a curb would primarily be governed by the mass and suspension properties of the vehicle, such that the body of the vehicle could be modeled as a rigid component. Although such a modeling assumption would be applicable to many vehicle types (e.g., Jeep, Geo Metro and other small cars with continuous body structures), it may not be appropriate for modeling pickup trucks where there is considerable compliance of the truck body parts (e.g., cab and bed) when crossing curbs. This fact limits the use of vehicle dynamics codes which only simulate the response of a sprung-mass system.

There are a number of variables that were considered for this study, such as vehicle type (e.g., small car, pickup, SUV, etc.), curb type, curb height, impact speed, angle of impact, as well as, tracking and non tracking impacts. It is not feasible, however, to conduct a complete matrix of simulations including all of these variables, thus the matrix of simulations shown in Table 1 will be used to investigate the effects of vehicles crossing curbs in a tracking manner.

The variables in the study matrix include five of the AASHTO curbs (i.e., Types A, B, C, D, and G) and the 100-mm New York curb. These curbs are shown in Figure 5.1. Two impact speeds will be used in the study: 70-km/hr and 100-km/hr. These speeds correspond to the intermediate speed range (i.e., 60 to 80 km/hr) and the high speed range (i.e., greater than 80 km/hr), respectively. Three angles of impact will also be investigated: 5-, 15- and 25-degrees. Impact angles of 5-degrees and 15-degrees represent the more probable range of impact angles, while the 25-degree impact is consistent with NCHRP Report 350 impact conditions for longitudinal barriers. The

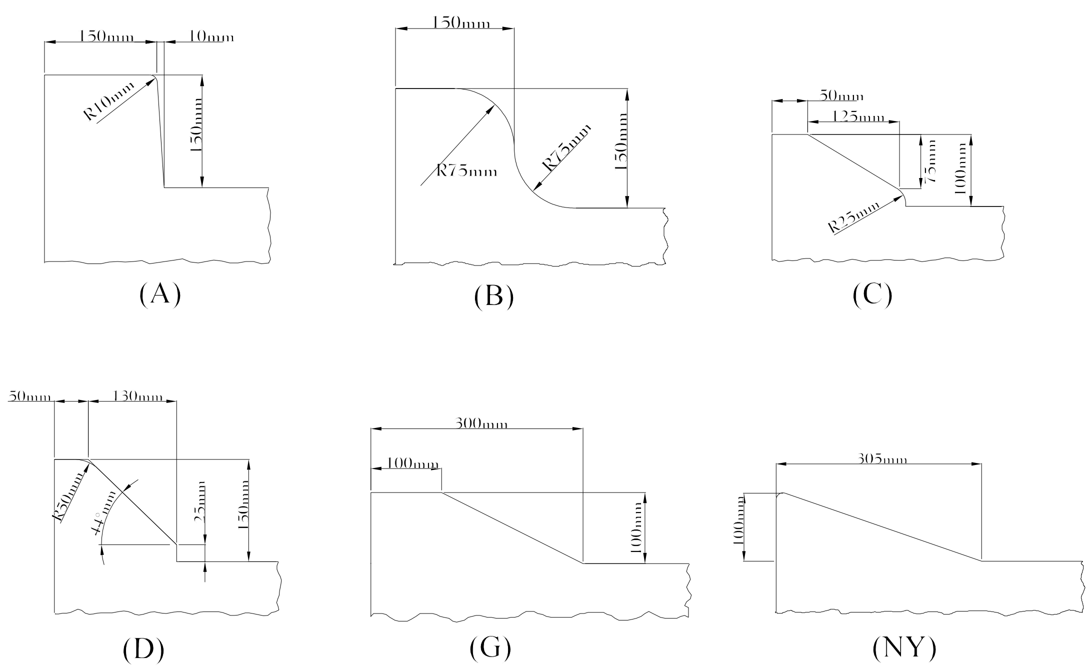


Figure 5.1: Curb types used in curb study.*(1)*

vehicle used in the simulations will be the 2000-kg C2500 pickup truck model developed by the National Crash Analysis Center with modifications made by Worcester Polytechnic Institute.*(69)*

Table 5.1: Matrix of simulations regarding vehicle speed and angle of impact for the 2000-kg pickup impacting AASHTO curbs in a tracking manner.

Curb Type	**Impact Speed = 70 km/hr**			**Impact Speed = 100 km/hr**		
	Angle of Impact			**Angle of Impact**		
	5 degrees	**15 degrees**	**25 degrees**	**5 degrees**	**15 degrees**	**25 degrees**
A	✔	✔	✔			
B	✔	✔	✔	✔	✔	✔
C	✔	✔	✔	✔	✔	✔
D	✔	✔	✔	✔	✔	✔
G	✔	✔	✔	✔	✔	✔
New York	✔	✔	✔	✔	✔	✔

5.3 Data Collected

The information collected from the analyses is being used to determine several important aspects of vehicle-response during and after interaction with curbs. The data that were collected are listed below and are included as Appendices of this report. They include:

1. Bumper trajectory,
2. Vehicle path,
3. Acceleration-time histories,

4. Yaw-, pitch- and roll-time histories,

5. Angle rate-time histories (yaw, pitch and roll),

6. Sequential snapshots of the impact event and

7. Test Risk Assessment Program Results.

5.3.1 Bumper Trajectory

For the case of a vehicle impacting a guardrail, the position of the front bumper can have a significant effect on the performance of the guardrail system. It has been shown by others that if the front bumper of a vehicle is above a critical point relative to a w-beam barrier, then the vehicle has a very high probability of overriding the guardrail.*(71)* The displacement-time history of a point on the top, right corner of the front bumper during a simulated event of the pickup truck model crossing a 150-mm type B curb at 100 km/hr

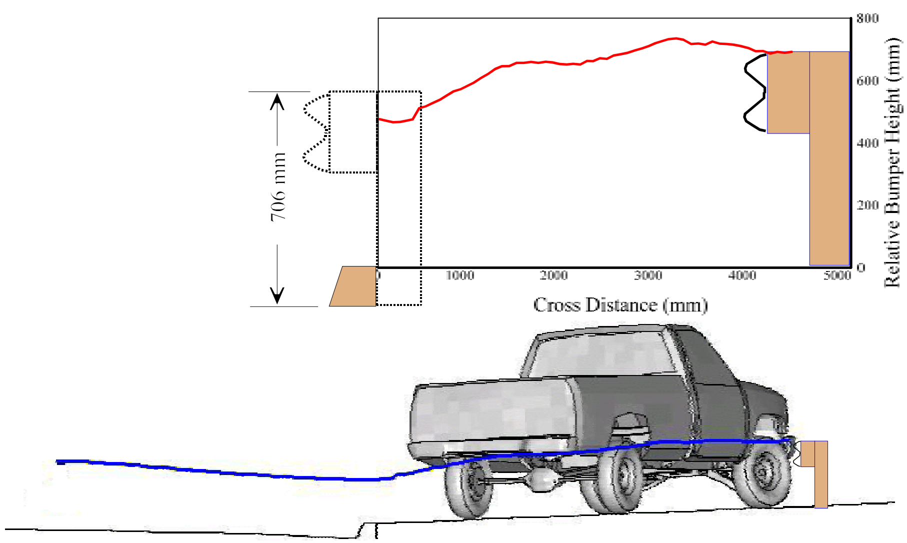


Figure 5.2: Front bumper trajectory plot from F.E. simulation of truck model crossing type B curb at 100 km/hr and 15 degrees.

is shown in Figure 5.2. The figure indicates that the trajectory of the bumper is continually increasing from the time of wheel impact until the front bumper reaches a point 3.3 m behind the curb. Furthermore, the height of the bumper exceeds the standard height of a strong-post guardrail (i.e., 685 mm) when the lateral position of the bumper is in the range from 1.5 m to almost 5 m behind the curb. Another phenomena that should be considered is underride of the guardrail. Such an event is not likely for the case of a 2000P pickup truck, however, it is likely during impact with vehicles such as small cars which have a low center of gravity and a low bumper height.

5.3.2 Vehicle Path

The path that a vehicle takes after impacting a curb is influenced greatly by the interaction between the tires and the curb face, as well as the forward momentum of the vehicle. A trace of the vehicle path obtained from the simulated event of the pickup truck model crossing a 150-mm type B curb at 100 km/hr is shown in Figure 5.3. The wheel-to-curb interaction is governed by two forces which tend to oppose each other: a normal force between the tire and the curb and the resulting frictional force. The normal force is the contact force between the tire and curb which acts normal to the curb face and tends to redirect the wheel along the longitudinal axis of the curb in the forward direction of the vehicle. The friction force between the tire and curb acts parallel to the curb opposing the forward motion of the vehicle which tends to steer the wheel into the curb. Regarding

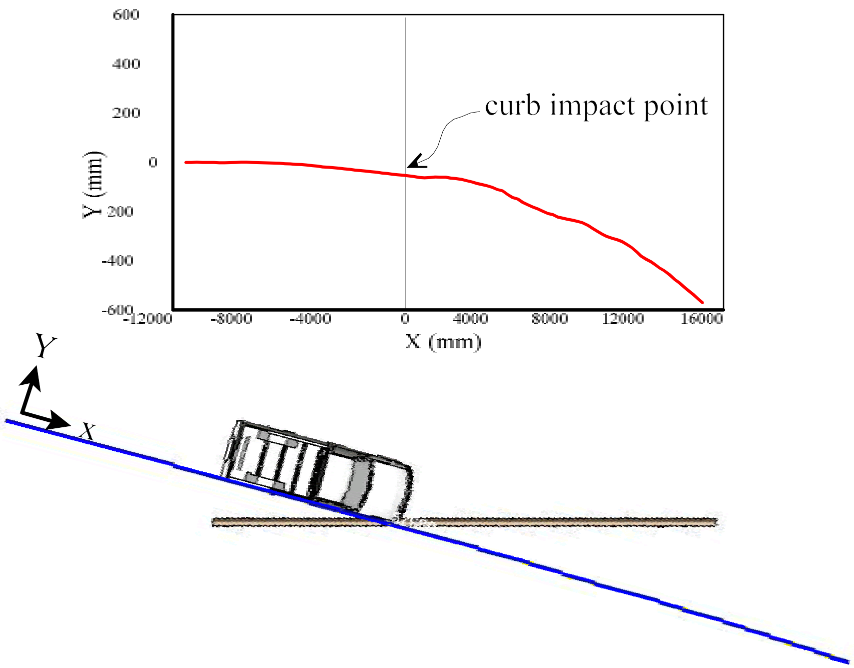


Figure 5.3: Overhead view showing front bumper trace from F.E. analysis of truck model crossing type B curb at 100 km/hr and 15 degrees.

vehicle speeds, such as those studied herein (i.e., 70-100 km/hr), neither the normal force nor the friction force will have much influence in deterring the vehicle from crossing the curb. They will, however, affect the steer angle of the front wheels as the vehicle traverses the curb and backfill area. For example, if the tire-curb interaction causes the wheels to steer abruptly it could cause vehicle instability and/or rollover. The steering system, therefore, plays a critical role in the response of a vehicle crossing a curb and must be considered in the analysis of vehicle-to-curb impacts.

In many of the previous studies, the wheel steer was not included in the analyses due primarily to limitations in computer software and lack of information regarding steering properties. In modern vehicle dynamics codes, options are available for including steering input, however, these inputs are limited to active wheel steer induced by a driver rather than reactive wheel steer caused by wheel interaction with an object.

The pickup truck model used in this study includes a steering system model that enables the front wheels to steer during impact as described in the thesis by Tiso.*(69)* Due to the lack of any experimental data on the steering properties of the vehicle, Tiso conducted some simple tests on a 1995 C2500 pickup truck in order to gain some insight into the basic response of the steering system. These tests were performed by 'jacking' up the pickup truck and applying a constant force perpendicular to the side wall of the driver's side front tire. Several tests were performed using two different values of applied load: 294 N and 392 N. Measurements of angular displacement and displacement rate of the wheel were taken and the data was used to determine effective properties of the steering mechanism, which were ultimately included in the finite element model. The resistance of the wheels to steer was modeled using a linear viscous element on the steering assembly. The damping constant for the viscous element was determined from his experiments to be 6.831 N/(mm/sec).

5.3.3 Acceleration-Time Histories

The acceleration-time histories of the vehicle will be collected at the center of gravity of the vehicle in a local coordinate frame that is fixed to the vehicle, as shown in Figure 5.4. These data will be processed such that useful information regarding occupant risk factors and vehicle kinematics can be determined.

5.3.4 Yaw-, Pitch- and Roll-Time Histories

Vehicular angular displacements and angular rates (i.e., yaw, pitch and roll) will also be collected at the center of gravity of the vehicle. These data will provide vital information regarding vehicle stability when crossing curbs. In addition they will indicate the probable approach angle and impact conditions of vehicle-to-barrier collisions when safety barriers are placed in conjunction with curbs.

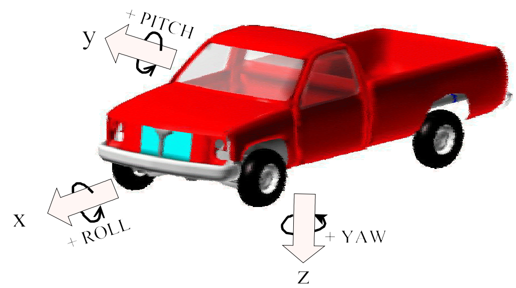


Figure 5.4: Vehicle fixed coordinate reference system.

5.3.5 Sequential Snapshots of Impact Event

Sequential snapshots from the analysis are presented in a curb-perspective view, a front view, a rear view and a top view. Each of these views are illustrated in Figure 5.5.

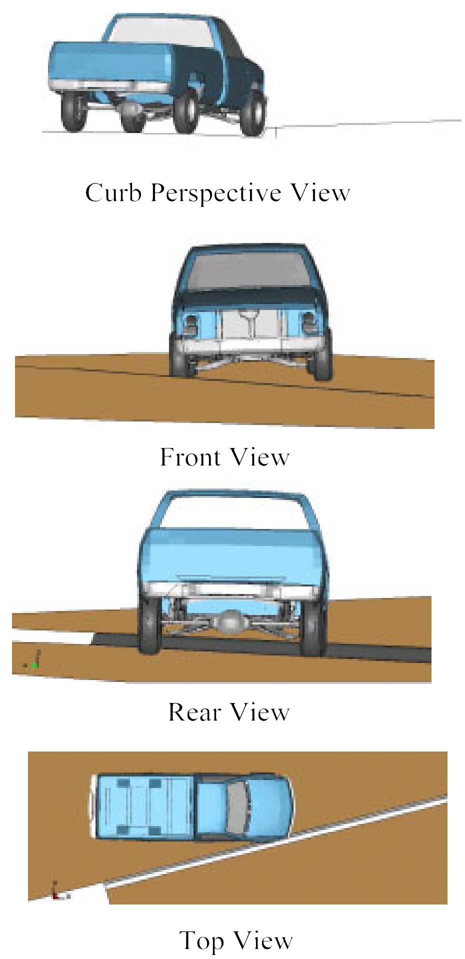


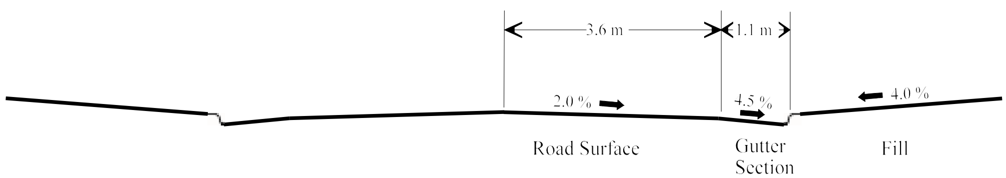
Figure 5.5: Typical view points for sequential snapshots taken from F.E. analyses.

5.3.6 Test Risk Assessment Program Results

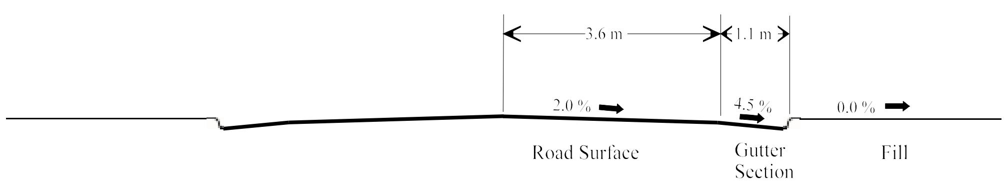
The acceleration-time history and displacement-time history data discussed above will be used in the Test Risk Assessment Program (TRAP) that was developed by the Texas Transportation Institute.*(46)* The TRAP program calculates standardized occupant risk factors from vehicle crash data in accordance with the National Cooperative Highway Research Program (NCHRP) guidelines and the European Committee for Standardization (CEN). Although occupant risk factors are expected to be low for the simple case of a vehicle crossing a curb, the data extracted from TRAP will provide a means of directly comparing the results from the matrix of simulations to each other. For example, the Acceleration Severity Index (ASI) values computed from each analysis case will be used to compare the severity of vehiclular motion during traversal of the curbs. The ASI is a nondimensional quantity whose value is calculated using a formula based upon the moving 50 ms average of vehicle accelerations in the x-, y- and z-directions and the limiting values of acceleration in each of the three directions.*(46)*

5.4 Finite Element Model of Curb and Terrain

There are many different scenarios for defining the cross section profile of a roadway (i.e., road surface, curbing and road shoulder). The geometry of the roadway profile may have a significant effect on the response of a vehicle traversing it. It would not be feasible to investigate every road-terrain scenario with every curb type, therefore only one roadway profile is being used in the parametric study. The Iowa Department of Transportation's <u>Road Design Details</u> for a two lane roadway with a 1.1-m curb section is shown in Figure 5.6a where the profile grade of the road surface is 2 percent, the gutter section has a grade of 4.5 percent and the backfill has a positive grade of 4 percent.*(72)* This roadway profile was selected because it represents a typical profile of roadway in which a curb and barrier may be installed together. It is recognized, however, that the backfill slope shown in Figure 5.6 may not represent a worse case scenario regarding a pickup truck crossing a curb and impacting a barrier where the vehicle overriding the barrier would be a major concern. For the purposes of this study a backfill with a 0% slope was adopted. The roadway profile used in this study is shown in Figure 5.6b.



a.



b.

Figure 5.6: **a.** Two-lane roadway detail with curb and gutter section from The Iowa Department of Transportation's Road Design Details.*(72)* and **b.** Cross section profile of roadway used in parametric analysis.

The roadway and curb are modeled using shell elements with rigid material properties. The tire-ground interaction is simulated in LS-DYNA using a surface-to-surface contact definition between the tire materials and the ground surface. Friction is included in the contact definition and is modeled based results from physical tests, in which a C2500 pickup truck was pulled over both an asphalt surface and a concrete surface. The wheels of the truck were “locked” as the vehicle was pulled at relatively low speed (i.e., approximately 1 km/hr). The force required to pull the truck was measured using a 5000 lb Sherline suspended hydraulic scale. The basic test setup is shown in Figure 5.7. The weight of the truck was 2196.5 kg (4842 lb).

Figure 5.7: Test setup for measuring friction force between tires and asphalt pavement using a Chevrolet 2500 pickup truck.

5.4.1 Results of the friction tests

For the case of truck on asphalt the load required to start the truck sliding was 4500 lb and the load required to keep the truck sliding at a constant speed was 4000 lb. Thus, the static coefficient of friction was approximately 0.93 and the dynamic coefficient of friction was 0.82. For the case of truck on concrete the friction values were even higher with a dynamic coefficient of friction between the truck tires and concrete measured to be approximately 0.93. In the finite element analysis, values for static and dynamic coefficients of friction between tires and ground of 0.93 and 0.82 were used, respectively.

An exponential function was used to smooth the transition between the static and kinetic coefficients of friction in LS-DYNA using the relationship

$$\mu = \mu + (\mu_s - \mu_k)e^{-d_v V_{relative}}$$

where μ_s is the static coefficient of friction, μ_k is the maximum kinetic coefficient of friction, d_v is the decay constant and $V_{relative}$ is the relative velocity between the contacting parts. The constant d_v was given a value of 0.75593E-04 seconds/mm which was obtained from a study conducted by Consolazio, et al. in which they back-calculated d_v from experimental data.*(73)*

5.5 Results of Parametric Study

The results of the finite element analyses are presented in the Appendices of this report. Animations of the impact events are provided on the NCHRP 22-17 project web site at: http://cee.wpi.edu/Roadsafe/Curbs/CURB_STUDY_AVIS/0%25backfill_slope/ . Summary tables and graphs of the results of the study are presented in the following sections of this report.

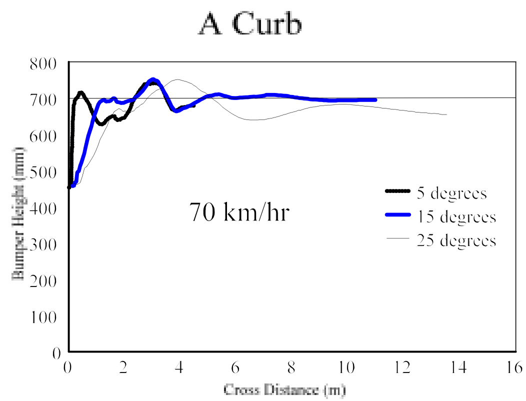
5.5.1 Front Bumper Trajectory

A summary of maximum bumper trajectory height with respect to the distance behind the curbs is shown in Figures 5.8 - 5.16. Figures 5.8 - 5.13 show the bumper trajectory height for each individual curb at the various impact speeds and impact angles, while Figures 5.14 - 5.16 show a relative comparison of the bumper height during impact with all the curbs for each individual impact condition.

From Figures 5.8 - 5.16 and Appendix I the following observations can be made regarding the potential for barrier override.

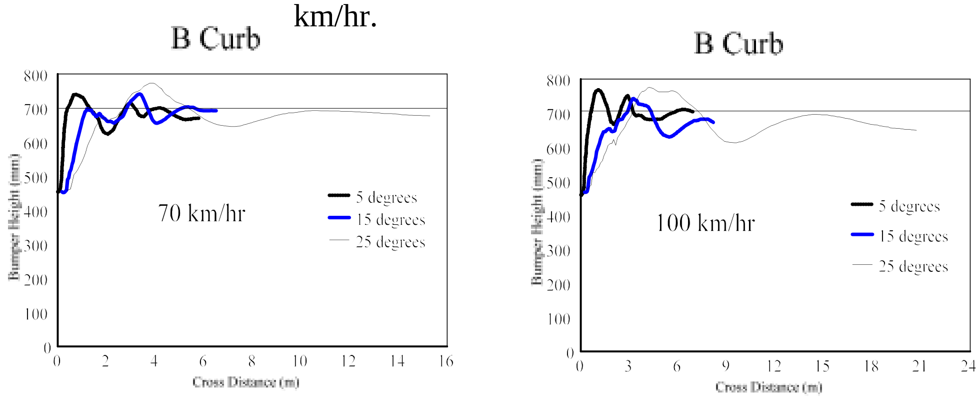
<u>Influence of lateral offset distance</u>

- For the 150-mm curbs (i.e., AASHTO types A, B and D) there is a potential for barrier override if the barrier is positioned within 8 m behind the curb.
- For the 100-mm curbs (i.e., AASHTO types C, G and the NY curb) the potential for barrier override appears to be less if the barrier is positioned between 2 m and 3 m behind the curb or at a distance greater than 8 m behind the curb. Although in the case of the 25-degree impacts, the trajectory of the front bumper is continuously increasing over a lateral distance of approximately 4 m behind the curbs.



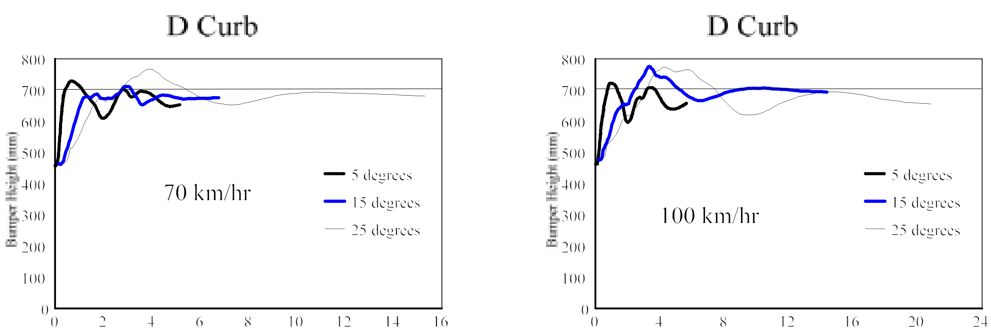
a

Figure 5.8: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing 150-mm AASHTO type A curb at 70 km/hr.



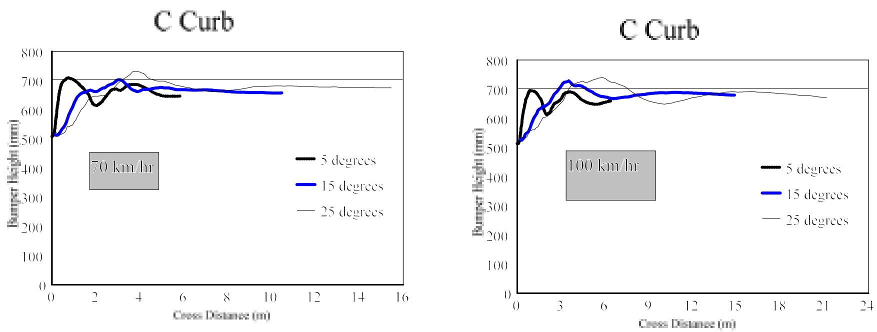
a b

Figure 5.9: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing 150-mm AASHTO type B curb at **a)** 70 km/hr and **b)** 100km/hr.



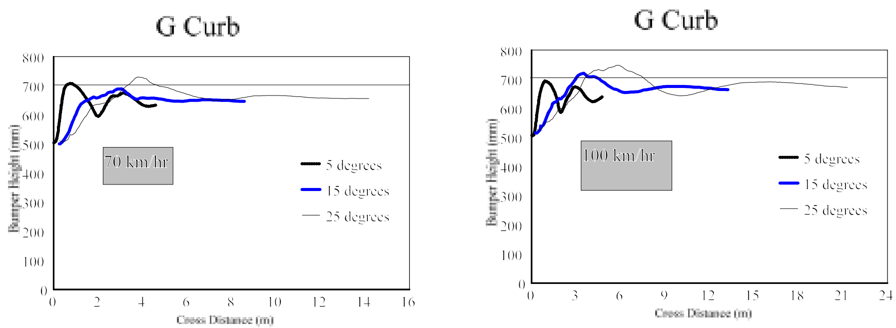
a b

Figure 5.10: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing 150-mm AASHTO type D curb at **a)** 70 km/hr and **b)** 100km/hr.



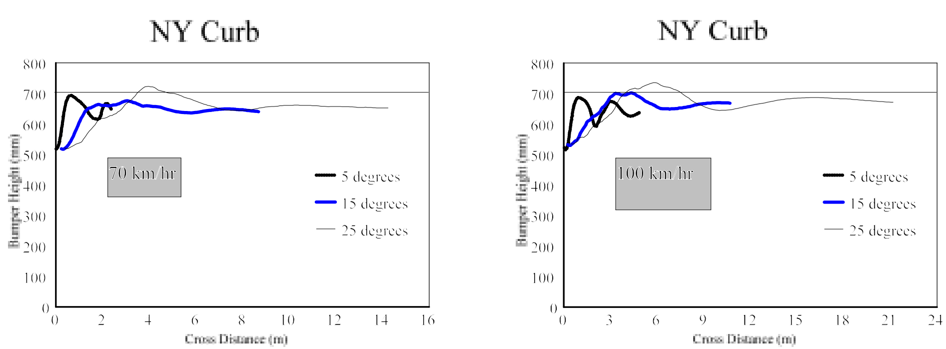
a b

Figure 5.11: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing 100-mm AASHTO type C curb at **a)** 70 km/hr and **b)** 100km/hr.



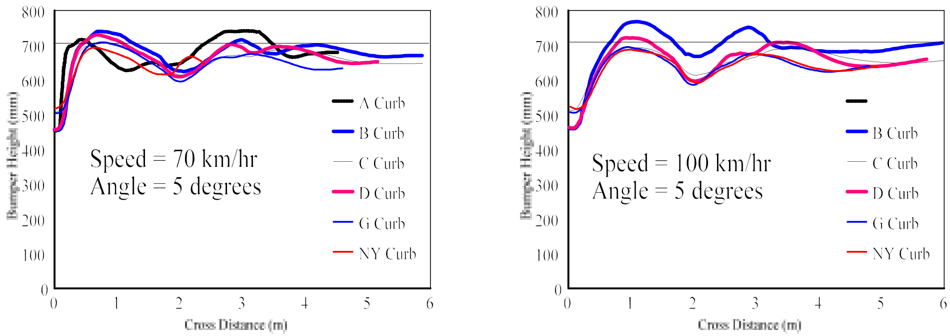
a b

Figure 5.12: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing 100-mm AASHTO type G curb at **a)** 70 km/hr and **b)** 100km/hr.



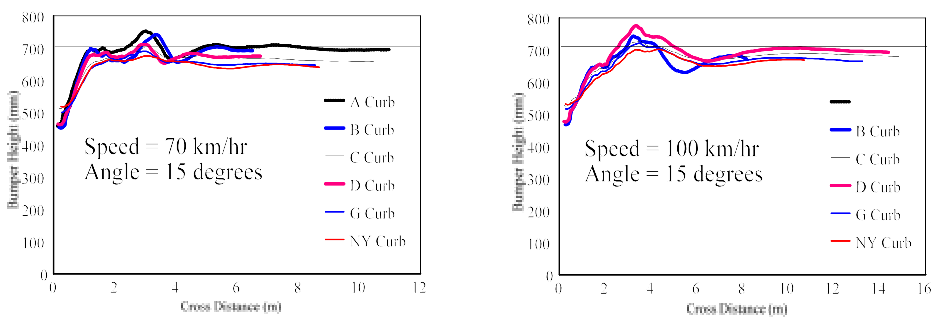
a b

Figure 5.13: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing 100-mm NY curb at **a)** 70 km/hr and **b)** 100km/hr.



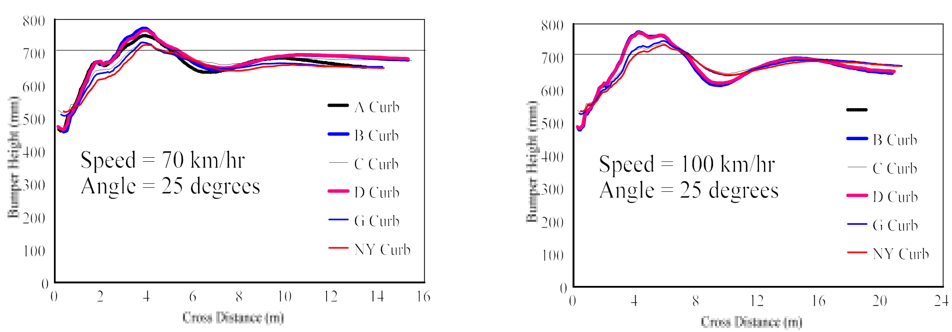
a. **b.**

Figure 5.14: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing each curb type at an angle of 5 degrees **a)** at 70 km/hr and **b)** at 100km/hr.



a. **b.**

Figure 5.15: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing each curb type at an angle of 15 degrees **a)** at 70 km/hr and **b)** at 100km/hr.



a. **b.**

Figure 5.16: Bumper height vs. lateral distance behind curb for C2500 Pickup crossing each curb type at 25 degrees **a)** at 70 km/hr and **b)** at 100km/hr.

Influence of impact conditions

- The trajectory of the front bumper is nearly independent of vehicle speed.
- The trajectory of the front bumper is slightly dependent on impact angle (i.e., increases with increase in impact angle; less so for the 150-mm curbs),
- For 100-mm curbs the potential for barrier override is minimal for impact angles of 5 and 15 degrees.
- For a given impact speed and angle the mode of vehicle trajectory is similar for all curb types (e.g., for a given impact speed and angle the maximum bumper trajectory occurs at approximately the same point, regardless of curb type).

Influence of curb shape

- The maximum value of bumper trajectory is dependent on curb height (i.e., increases with increase in curb height),
- Bumper trajectory is slightly dependent on slope of curb face, with some discrepancy in the results from the AASHTO curb type A analyses.

5.5.2 Vehicle Kinematics and TRAP Results

The accelerations and angle displacement-rates, computed at the center of gravity of the vehicle model, were extracted from the results of the finite element analyses and were input into TRAP. From these data occupant risk factors were computed based on occupant impact velocities and occupant ridedown accelerations and were found to be minor (as expected). The primary purpose for using TRAP, however, was to obtain information that would aid in the development of a quantified comparison of vehicle stability (or lack of) between each analysis regarding the various curb types.

The stability of the vehicle during and after interaction with curbs may be adversely affected by wheel interaction with the curbs. For example, the front wheels of a vehicle may undergo abrupt steering during impact with a curb which may eventually lead to spin-out or overturn of the vehicle. TRAP provides information based on maximum accelerations, maximum angle displacements and maximum displacements rates which may be useful in discerning vehicle instability. A summary of the results from TRAP for each analysis in the study matrix are tabulated below in Table 2 and some of the data are presented graphically in Figures 5.17 - 5.19.

<u>ASI Values</u>- Figures 5.17 and 5.18 shows a comparison of the ASI for each analysis (note: curb types A, B and D are 150-mm curbs and curb types C, G and NY are 100-mm curbs). The Acceleration Severity Index (ASI) value computed from each analysis is relatively low concerning occupant risk during impact, but they do give an indication of the overall acceleration response of the vehicle during vehicle-curb interaction which may be regarded as some measure of difficulty for a driver to maintain control of the vehicle. For example, a higher ASI value indicates that the vehicle will experience higher accelerations which may affect the drivers ability to maintain control of the steering and braking of the vehicle during impact.

From Figures 5.17 and 5.18 it can be concluded that ASI values:

! Increase as impact velocity increases,
! Increase as impact angle increases,
! Increase as the curb height increases, and
! Increase as the slope of the curb face increases.

Figure 5.19 shows the maximum angular displacements and maximum angular displacement rates from each analysis case, from which the following observations can be made (refer to table 5.2 for details).

Roll angles:

! minimal for all cases (e.g., less than 8 degrees),

! slope of curb face has no discernable influence, especially at higher impact speeds,

! increase as curb height increases,

! impact speed has minimal influence,

! decrease as impact angle increases.

Roll rates:

! increase as curb height increases,

! independent of slope of curb face,

! impact speed has minimal influence,

! increase as impact angle increases (the influence of impact angle on roll rates is much more pronounced for cases involving 150-mm curbs than for cases involving 100-mm curbs).

Table 5.2: Summary of results from TRAP for each analysis in the curb study matrix.

Curb Type		Impact Conditions		Max. Vertical Acceleration (G's)			Max. Vertical Impulse (N*s)	ASI	Max. Angle Displacements (degrees)			Max. Angle Disp. Rates (deg/s)		
		Speed (km/hr)	Angle (deg)	60 Hz Filter	10 ms average	50 ms average			Roll	Pitch	Yaw	Roll Rate	Pitch Rate	Yaw Rate
150 mm Curbs	**A**	**70**	**5**	6.31	3.21	1.05	1618	0.18	-6.4	3.0	22.6	68.2	36.2	35.2
			15	7.73	4.01	1.36	2170	0.20	-6.5	3.1	27.4	77.0	50.3	40.9
			25	9.41	4.11	1.77	3519	0.22	-5.4	2.4	12.0	82.3	69.0	38.0
	B	**70**	**5**	5.08	1.00	2.57	1785	0.11	-6.9	2.4	20.2	46.1	28.3	47.2
			15	7.38	3.88	1.42	5238	0.19	-6.6	3.3	25.2	67.5	54.4	47.2
			25	6.59	5.47	1.92	3453	0.25	-5.4	2.8	26.9	116.0	34.1	44.3
		100	**5**	4.44	2.72	1.07	2523	0.19	-7.6	2.3	21.4	62.4	27.8	34.6
			15	6.79	4.65	1.39	2517	0.22	-5.0	2.6	-20.0	80.7	39.9	37.2
			25	14.93	10.00	2.84	4284	0.29	-4.2	2.4	23.1	97.5	71.6	57.1
	D	**70**	**5**	1.50	1.25	0.90	1506	0.10	-7.4	2.2	11.1	45.8	17.9	22.7
			15	3.58	2.63	1.31	1990	0.14	-5.4	2.6	-8.4	63.4	34.4	32.7
			25	7.56	5.57	1.75	3349	0.21	-5.2	2.7	28.1	100.7	38.8	39.7
		100	**5**	2.55	1.40	0.87	2115	0.14	-7.1	1.8	7.8	45.3	13.4	26.9
			15	5.78	4.51	1.17	2443	0.19	-5.3	2.8	24.6	72.9	37.7	37.6
			25	11.41	7.19	2.54	3772	0.26	-4.2	2.4	23.8	95.8	57.5	51.1
100 mm Curbs	**C**	**70**	**5**	1.30	0.97	0.63	1318	0.09	-6.0	1.6	12.6	37.9	12.2	18.9
			15	2.86	1.73	0.95	1557	0.11	-4.2	2.1	11.4	36.4	22.9	21.7
			25	3.93	2.42	1.20	2411	0.16	-3.9	2.5	23.7	48.2	23.0	28.7
		100	**5**	1.50	1.03	0.70	1594	0.09	-5.7	1.4	9.1	36.8	12.1	17.9
			15	3.20	2.06	1.00	1990	0.15	-3.8	2.3	22.8	50.1	22.8	23.5
			25	5.86	4.54	1.25	2500	0.18	-3.4	2.0	23.7	61.1	28.0	27.8
	G	**70**	**5**	0.83	0.77	0.61	1097	0.07	-5.9	1.6	6.4	35.9	12.3	15.8
			15	2.17	1.41	0.85	1811	0.09	-4.0	2.2	4.1	36.1	17.9	17.5
			25	4.20	2.73	1.14	2319	0.14	-4.1	2.7	9.8	54.7	24.6	20.1
		100	**5**	0.99	0.89	0.74	1589	0.08	-5.4	1.3	3.3	37.7	12.1	13.1
			15	2.59	1.81	1.06	1973	0.12	-4.0	2.4	6.7	47.8	26.6	16.8
			25	7.81	5.87	1.81	2585	0.19	-3.6	2.2	21.7	66.2	26.9	29.0
	NY	**70**	**5**	0.43	0.34	0.26	7.96	0.05	-4.9	1.2	4.0	27.8	12.2	15.8
			15	1.30	0.84	0.63	1188	0.07	-3.8	2.1	3.0	32.3	14.5	12.5
			25	3.10	2.00	1.11	2017	0.14	-3.7	2.3	-7.8	35.0	25.1	16.2
		100	**5**	0.96	0.88	0.71	1477	0.08	-5.5	1.2	4.1	37.6	12.1	10.6
			15	1.72	1.43	0.97	1626	0.10	-3.7	2.0	5.9	29.2	19.0	13.3
			25	5.23	4.45	1.59	2313	0.17	-3.4	2.1	18.4	57.7	22.3	19.3

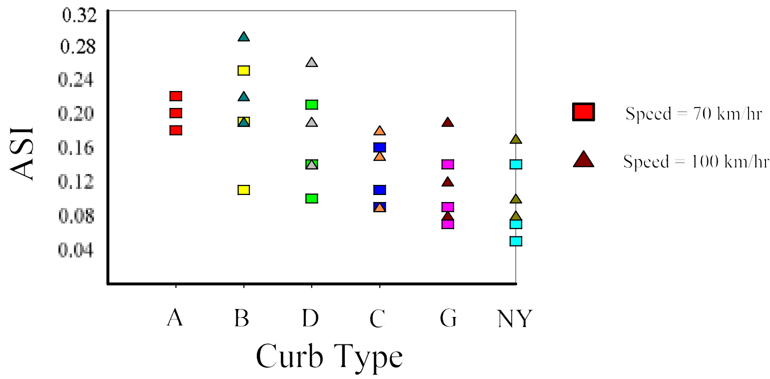


Figure 5.17: ASI vs. curb type from finite element analyses for each impact condition.

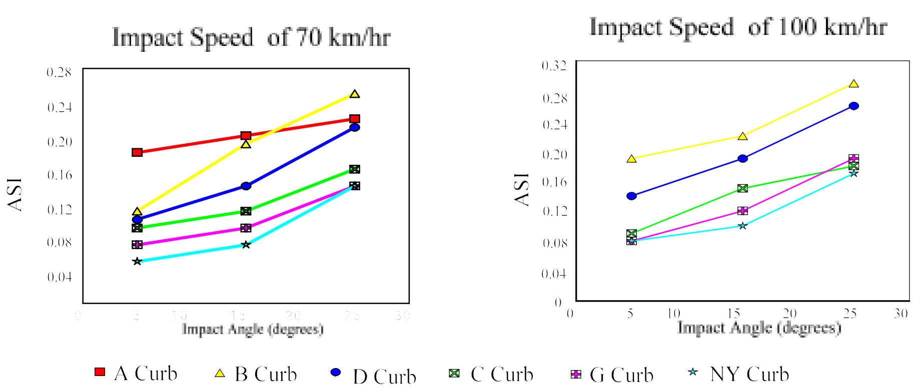


Figure 5.18: ASI vs. impact angle for each curb type from finite element analyses.

Pitch angles:

- ! minimal for all cases (e.g., less than 3.5 degrees),
- ! increase slightly as curb height increases,
- ! slope of curb face has no discernable influence,
- ! independent of impact speed

Pitch rates:

- ! independent of impact speed.
- ! for the case of 150-mm curbs
  - " pitch rates vary significantly with respect to impact angle, and
  - " slope of curb face has no discernable influence.
- ! for the case of 100-mm curbs
  - " pitch rates are much less influenced by impact angle, and
  - " are independent of the slope of the curb face.

Yaw angles:

NOTE: The steer angle of the front wheels after impact with a curb is the primary factor affecting yaw angle of the vehicle. The front wheels steer out, usually to the right, during wheel-curb interaction, therefore, the yaw angle increases as the analysis continues and is typically greatest at the end of the analysis. The yaw angle may be more useful for determining impact conditions for barriers placed behind curbs than for determining vehicle spinout (in which other factors need to be evaluated). For example, consider a barrier offset some distance behind a curb and assume a vehicle encroaches upon the curb-barrier system at some angle. As the vehicle traverses the curb the resulting yaw angle of the vehicle may lead to an impact with the barrier at a higher or lower impact angle than the original encroachment angle.

In order to discern if the vehicle is unstable (spin-out) after traversing a curb it is necessary to consider the magnitude of yaw rate (e.g., the maximum yaw rate generally occurs during wheel-curb interaction) and also to consider the tracking behavior of the wheels (i.e., determine if the paths of the rear wheels are consistent with the front wheels).

- Yaw angle magnitude increases as slope of curb face increases.
- Curb height has minimal or no influence.
- Yaw angle magnitude is independent of impact speed.
- For the case of 150-mm curb types, yaw angle ranges from -8 to 28 degrees and varies erratically with respect to impact angle,
- For the case of 100-mm curb types
  - AASHTO C curb: Yaw angle ranges between 9 and 24 degrees
  - AASHTO G curb: Yaw angles are very low (e.g., 3 - 10 degrees) except for high speed, high angle impact for which the max yaw angle was 22 degrees.
  - 100-mm New York curb: Yaw angles are very low (3 - 6 degrees, and negative 8 degrees in one case) except for high speed, high angle impact for which the max yaw angle was 18 degrees.

Yaw rates:

- increase as the height of curb increases,
- increase as the slope of the curb face increases,
- For the case of 150-mm curbs
  - AASHTO A curb: Influence of impact angle on yaw rate is not discernable.
  - AASHTO B Curb: Yaw rate varies significantly and erratically with respect to impact speed, however, impact angle has minimal influence on yaw rate (with the exception of one case:100 km/hr, 25 degree impact)
  - AASHTO D Curb: Yaw rate increases as impact angle increases, and yaw rate increases only slightly as impact speed increases.
- For the case of 100-mm curbs, impact conditions have minimal influence on yaw rate
  - Independent of impact speed
  - Slight increase in yaw rate as impact angle increases

5.6 Additional Modifications to Vehicle Model and Subsequent Results

After the curb tracking study was completed some new data regarding shock absorber properties were obtained. This section details those findings and discusses their effect on vehicle response and also how they affect the results presented in section 5.5.

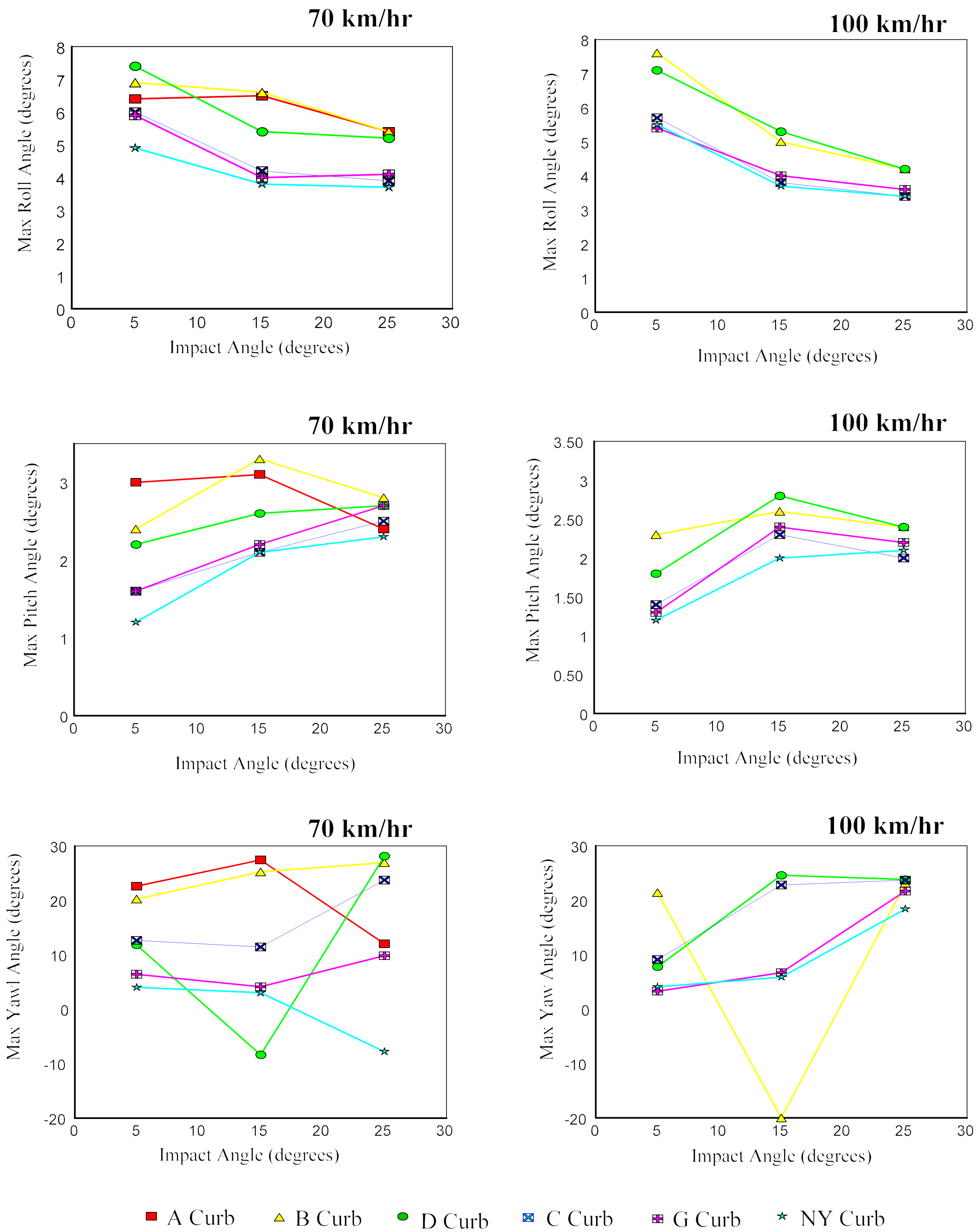


Figure 5.19: Maximum roll, pitch and yaw angle displacements of the pickup versus impact angle.

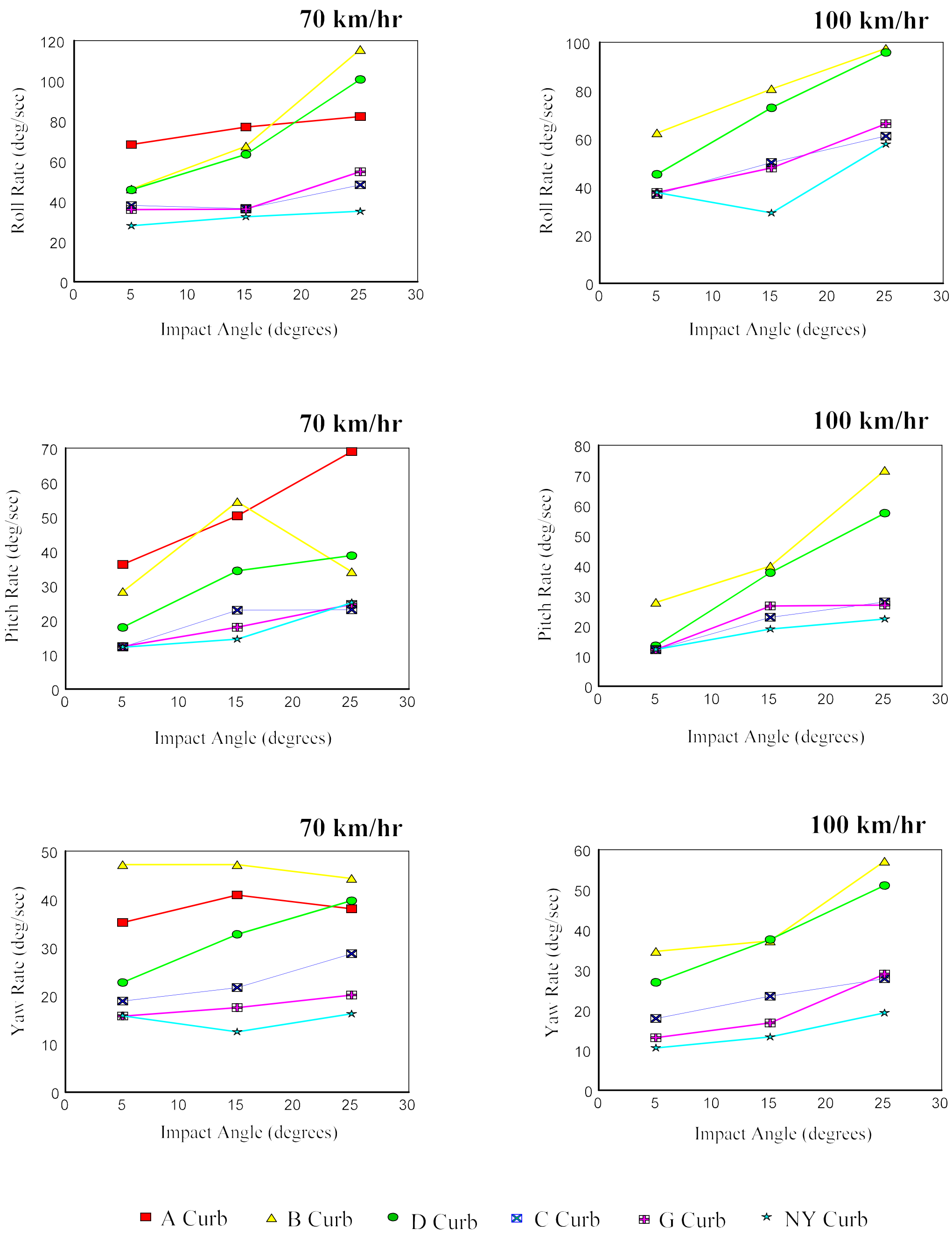


Figure 5.20: Maximum roll, pitch and yaw rates of the pickup versus impact angle.

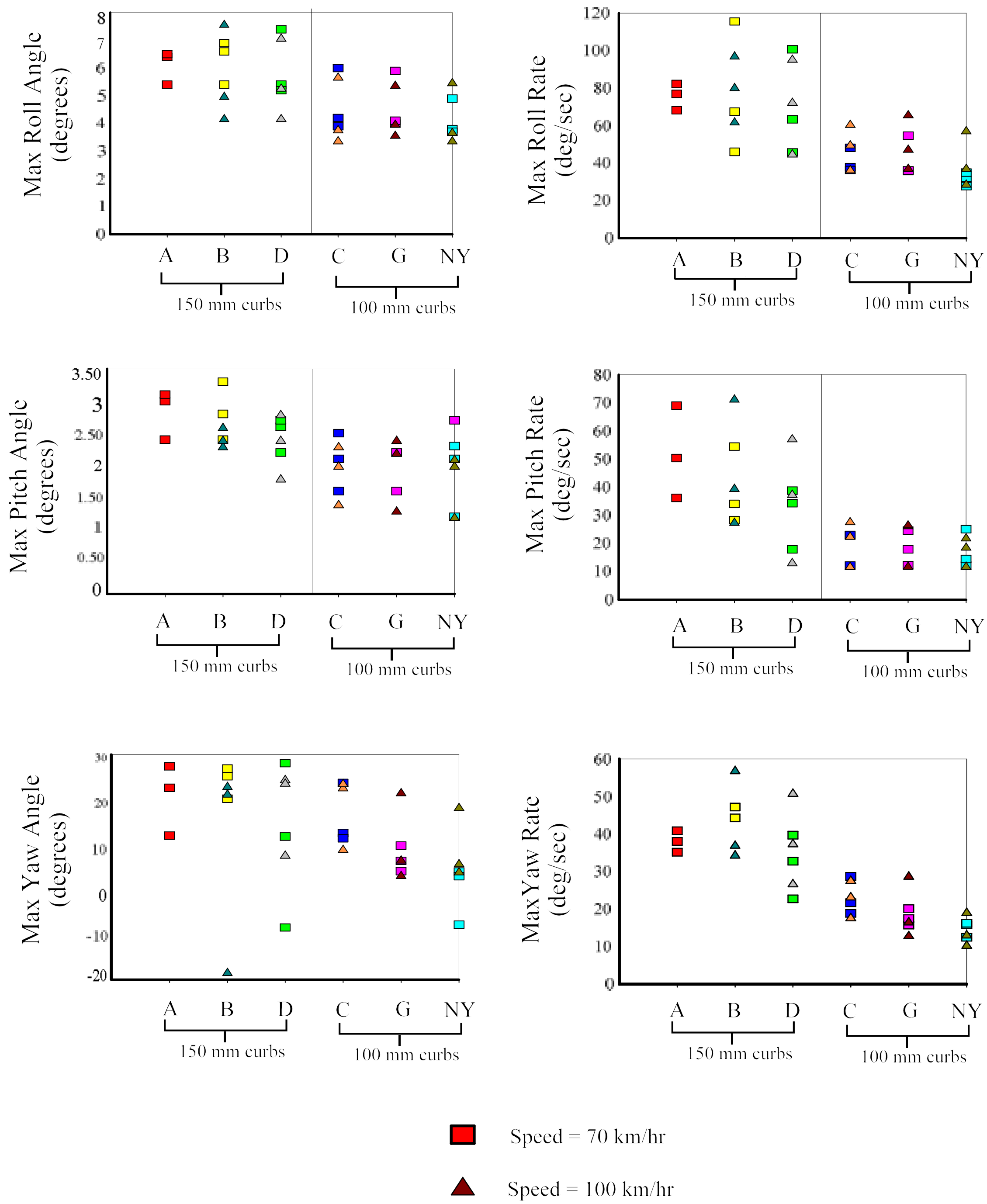


Figure 5.21: Maximum angular displacements and displacement rates with respect to curb type and impact speed.

In an earlier phase of NCHRP project 22-17 (i.e., the sponsor of this research) many of the suspension components of a Chevrolet 2500 pickup were purchased and tested in the WPI laboratories in order to determine accurate properties for those components.*(69)* There were no equipment available, however, to test shock absorbers throughout the complete range of motion and velocity that they are expected to experience in curb impacts. It was therefore necessary to rely on shock absorber properties obtained from a manufacturer to incorporate into the model.

Recently, a testing device was constructed at WPI which allowed for some crude tests to be conducted on the shock absorbers. The test device is shown in Figure 5.22. It is simply a drop tower that was designed and constructed by a former graduate student at WPI.*(74)* Although the test setup was rather crude, the data obtained from the tests were considered reliable for application in the pickup model.

The data needed from the tests to define shock absorber properties are force vs. velocity. The tests were performed by attaching one end of a shock absorber to a stationary cable, while the other end was attached to a weight held initially in place by locks. When the lock is removed the weight will accelerate under gravity load until it reaches a constant velocity due to the resistance of the shock. Two sets of data were collected in the tests: displacement-time history was obtained from a displacement transducer which was fixed to the bottom of the drop tower with the "string" connected to the falling plate and acceleration-time history was obtained from an accelerometer placed on top of the falling

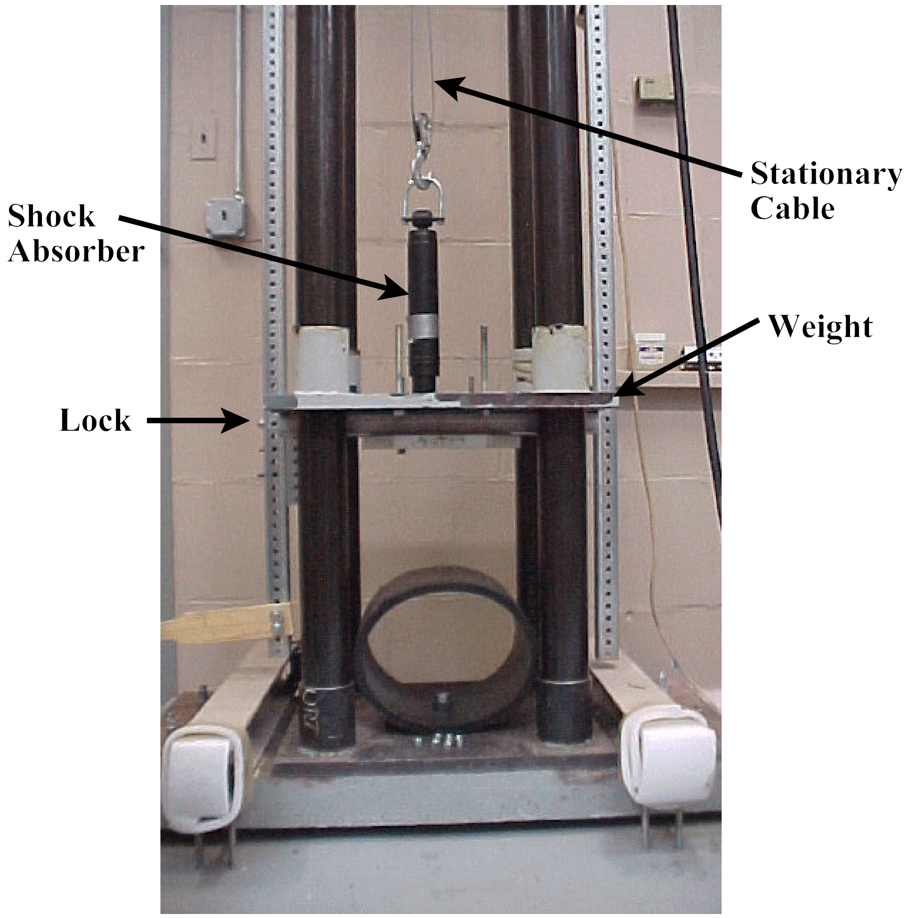


Figure 5.22: Test device used for measuring shock absorber properties

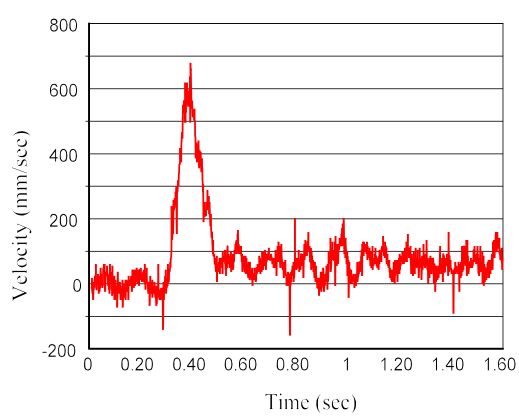


Figure 5.23: Velocity-time history from shock absorber test.

plate. The acceleration data was used primarily to verify that the device reached a zero acceleration (i.e., constant velocity). The displacement data was differentiated and filtered in order to obtain velocity. An example of the velocity-time history data is shown in Figure 5.23. One data point was collected from each test (i.e., the weight of the falling plate and the velocity after it reached a constant value which was 761 N at 64.7 mm/s for the case shown in Figure 5.23). Additional weight was then added and the test repeated.

Three new rear shock absorbers were purchased for testing: one was an after-market brand and two were Chevrolet products. Also, a shock absorber was removed from the rear of the 1995 Chevrolet C2500 pickup truck used in the testing program.*(69)* One of the Chevrolet brand shock absorbers was faulty and was not used in the tests. The results from the tests are shown in Figure 5.24a and are compared to the results provided by the manufacturer in Figure 5.24b. As you can see in Figure 5.24a there is considerable difference in the properties of the new shocks compared to the old shock that was taken off of the 1995 Chevrolet 2500, but the real surprise was the difference in the manufacturer data compared to the lab test results in Figure 5.24b.

The properties that were obtained in the laboratory from the shock absorber taken from the 1995 pickup truck, were included in the C2500 model and a simulation was conducted in which the rear wheels of the vehicle were set up on a 220 mm high box. The truck model was then given an initial velocity and, as the truck rolled off the box, displacement-time history data between a point on the frame of the truck and the rear axle

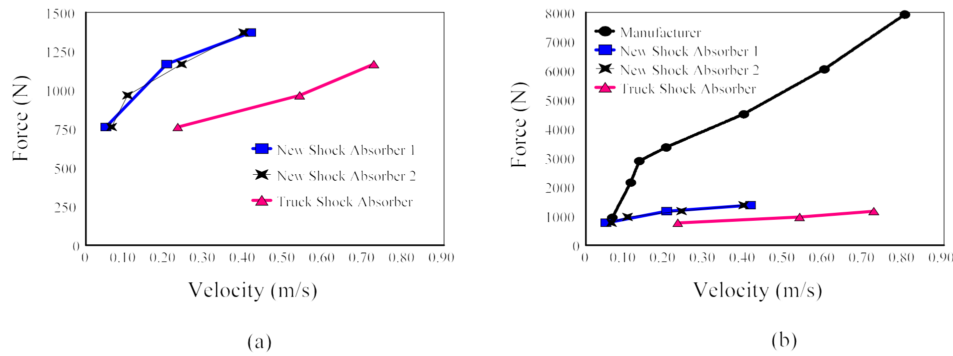


Figure 5.24: Force-velocity properties (a) obtained from laboratory tests and (b) laboratory tests compared with manufacturer data.

was collected. This data was compared to the results of the full-scale tests conducted in Tiso's study.*(69)*

Figure 5.25 was taken from Tiso's Thesis and shows the results of two full-scale drop tests, a computer simulation using the original NCAC C2500 model and a simulation using the modified NCAC model (which contained shock absorber properties from the manufacturer). The response of the modified C2500 model accurately captures the initial displacement (which is governed primarily by the suspension springs) but does not accurately represent the behavior of the rebound response which is oscillatory in the tests and damps out very quickly in the simulation.

Figure 5.26 shows the results of the simulation of the modified C2500 pickup model using the shock absorber properties measured in laboratory from the shock absorber taken from the rear of the vehicle used in the tests compared to the two full-scale drop

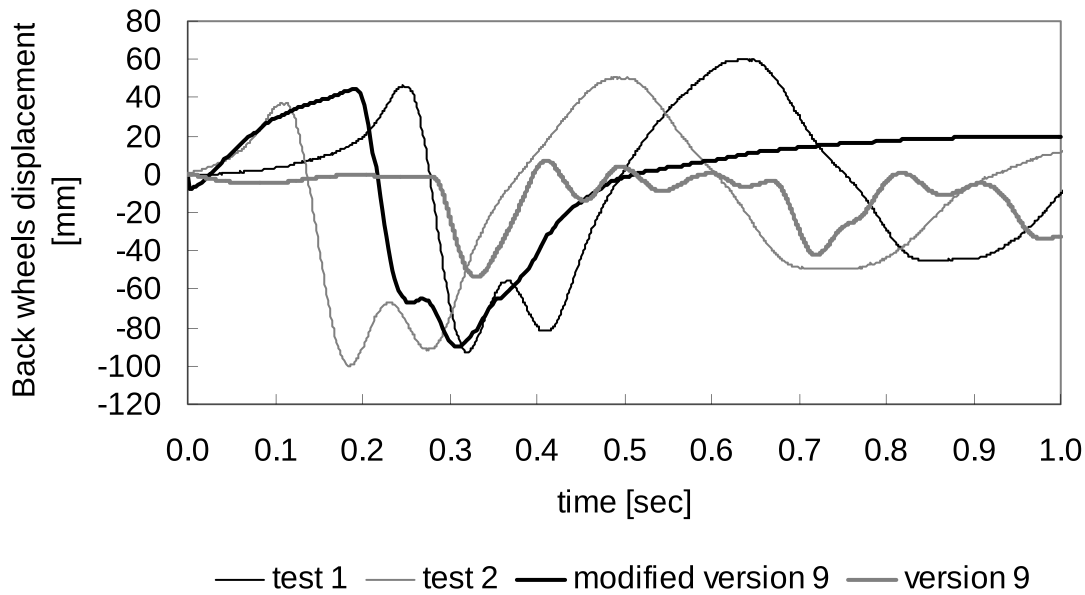


Figure 5.25: Roll off drop test comparison for finite element simulations and full-scale tests *(69)*

tests. In this case the response of the model corresponds very well to the tests throughout the event.

The shock absorber properties that were measured in the laboratory from the new Chevrolet brand shock absorber were incorporated into the finite element model of the vehicle in the curb traversal study. A select number of cases from the curb traversal were then rerun to determine the effects of these modifications. The cases which were rerun included:

1) 150-mm AASHTO type B curb; impact speed of 70 km/hr; angle 25 degrees
2) 100-mm AASHTO type C curb; impact speed of 70 km/hr; angle 25 degrees
3) 100-mm AASHTO type C curb; impact speed of 100 km/hr; angle 25 degrees

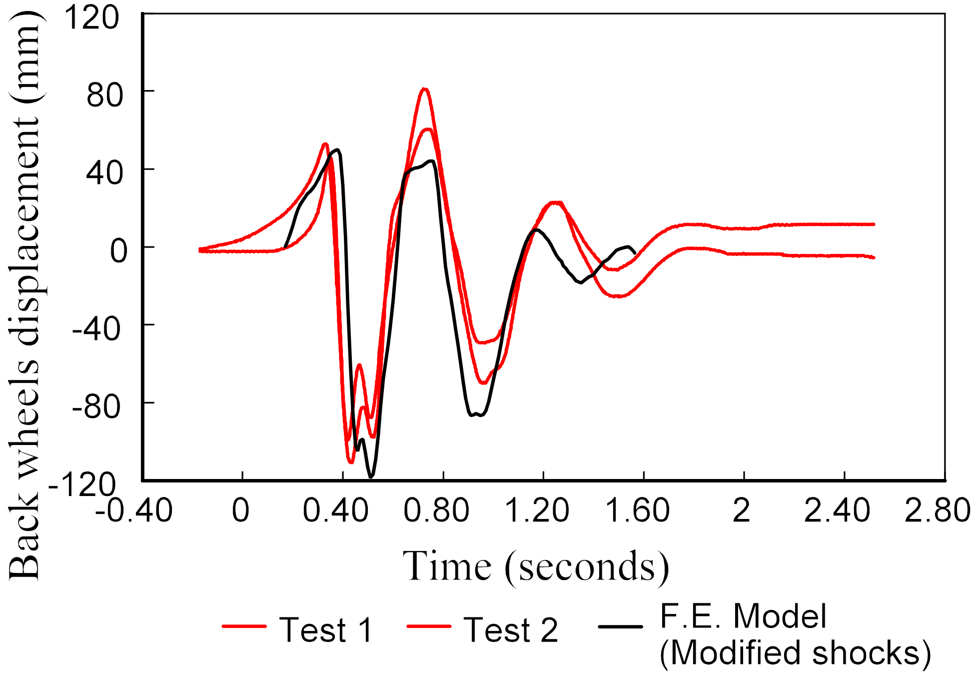


Figure 5.26: Roll off drop test comparison between C2500 pickup model with modified shock absorber properties and full-scale crash tests.

4) 100–mm AASHTO type G curb; impact speed of 70 km/hr; angle 25 degrees

5) 100-mm AASHTO type G curb; impact speed of 100 km/hr;angle 25 degrees

The results from those analyses were obtained and processed but only a portion of the data was documented.[1] The bumper trajectory results from an analysis in which the vehicle traverses the 150 mm high AASHTO type B curb is compared to the results from the original model in Figure 5.27. The magnitude of bumper trajectory is higher in the analysis containing the modified shock absorber properties, but the trajectory mode is essentially the same (e.g., the peaks occur at the same time). Furthermore, the maximum

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[1] Data was lost due to computer hardware failure.

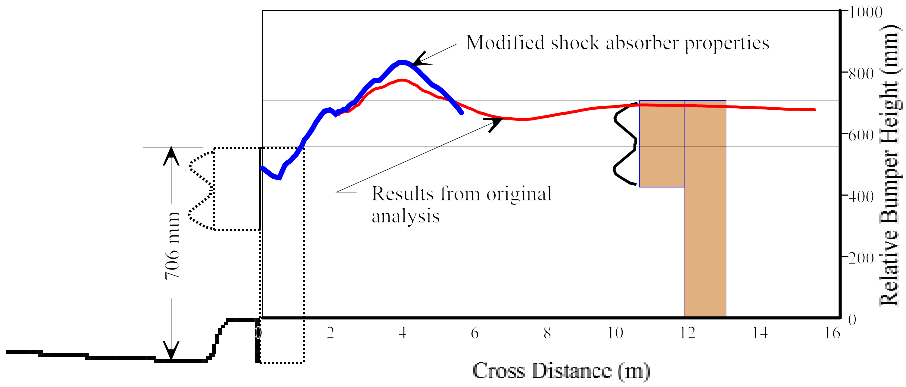

Figure 5.27: Front bumper trajectory results from original analysis and analysis involving modified shock absorber properties for the case of the C2500R traversing the 150-mm AASHTO type B curb at 70 km/hr.

roll, pitch and yaw angles during impact were approximately the same in both analyses. The effects that the modified shock absorber properties had on the results of the vehicle response in this analysis was consistent in each of the other analyses involving the modified shock absorber properties.

5.7 Summary

The finite element program LS-DYNA was used in a parametric study to investigate the influence of several factors regarding vehicle stability and trajectory when traversing curbs. The variables used in the study included curb height, curb shape, impact speed and impact angle. The vehicle model used in the study was the modified NCAC finite element model of the C2500 pickup truck (see chapter 4 for details). The roadway was modeled as a flat grade section with a 2 percent cross-slope. The gutter section was modeled with a 4.5 percent cross-slope and the backfill terrain was modeled as a flat surface. Six curb types were used in the study including five AASHTO curbs (i.e., Types

A, B, C, D and G) and the 100-mm New York curb.

The data collected in the analyses include bumper trajectory, vehicle path, acceleration-time histories, angular displacement-time histories, angular rate-time histories, sequential snapshots of the impact event, and occupant risk information using the Test Risk Assessment Program.

The results of the study indicate that the trajectory of the front bumper is only slightly affected by impact speed and angle and, that the slope of the curb face has little influence on trajectory as well. The most significant factor influencing trajectory is the height of the curb. However, based on the range of impact conditions considered in this study, the trajectory of a 2000-kg pickup truck traversing curbs with a height of 100 and 150 mm was considered sufficient to override a standard strong-post guardrail placed at 0.5 m to 8 m behind the curb.

The results of the Test Risk Assessment Program (TRAP) using acceleration and angular rate data collected at the center of gravity of the vehicle model during the analysis indicated that ASI values were proportional to impact speed, impact angle, curb height and the slope of the curb face. This suggests that a lower curb with a more mild sloping face (e.g., 100-mm New York curb) is much less likely to cause a driver to loose control of a vehicle when traversing the curb than would be the case if a taller steep faced curb such as the AASHTO type A or B were used.

The basic conclusions that can be made from the analysis results are that vehicle impacts with roadside curbs can often result in the driver losing control of the vehicle. There are many factors that influence vehicle behavior during such an event, such as abrupt steering caused by the interaction of the front wheels with the curb, loss of contact between the tires and ground, excessive vehicle accelerations and excessive roll, pitch and yaw rates of the vehicle during impact. Each of these factors may lead to loss of control of the vehicle, however, total loss of control is unlikely except in extreme cases. A more important issue may be the effects that these factors precipitate when curbs are placed in combination with roadside barriers (e.g., guardrail, crash cushions, breakaway poles, etc). For example, the trajectory of a vehicle after crossing a curb may be insignificant regarding the potential for losing control of the vehicle, but even a slight change in vertical trajectory may be sufficient to cause the vehicle to impact a roadside safety device at a point higher or lower than normal, which may lead to override or underride of roadside barriers or may adversely affect the breakaway mechanism of various roadside hardware devices. A more complete synthesis of the results of the curb traversal study will be presented in chapter 7.