VI. VEHICLE IMPACT WITH CURB-AND-GUARDRAIL SYSTEMS

6.1 Introduction

It is often necessary to use a curb at a particular location that also warrants a traffic barrier. Inadequate design of these curb-and-barrier combination systems can result in vehicles vaulting or under-riding the barrier. While the use of curbs is discouraged on high-speed roadways, they are often required because of restricted right-of-way, drainage considerations, access control, delineation and other curb functions. Curb-and-barrier installations are currently being put in place without a clear understanding of the effects that such combinations will have on the ability of the barrier to safely contain and redirect an errant vehicle. There have been a very limited number of full-scale crash tests on curb-and-barrier combinations and a large percentage of those tests involving the larger class of passenger vehicles, such as the 2000-kg pickup truck, were unsuccessful.*(28)* Even the cases involving the 2000-kg pickup truck that satisfied the requirements of NCHRP Report 350 resulted in excessive damage to the barrier system or extreme trajectories and instability of the vehicle.*(29)(30)(32)*

This chapter discusses the analysis of various curb-and-barrier systems subjected to impact by a 2000 kg pickup truck (i.e., modified NCAC C2500R pickup truck model) under three different impact conditions:

1) 100 km/hr and 25 degrees (i.e., NCHRP Report 350 Test 3-11),

2) 85 km/hr and 25 degrees and

3) 70 km/hr and 25 degrees (i.e., NCHRP Report 350 Test 2-11) .

The study includes the modified G4(1S) guardrail installed in combination with five curb types (i.e., AASHTO types B, C, D, G and the 100-mm New York Curb). The analyses are carried out using the finite element program LS-DYNA and are designed to investigate the effects of curb type, curb placement and impact speed on the performance of the barrier system.

6.2 Parametric Study

The modified G4(1S) guardrail model and the modified NCAC C2500R pickup model (refer to Chapter 4) will be used to determine the impact response of guardrail placed in combination with various types of curbs. There are a limited number of analyses that can be conducted due to feasibility and time constraints, however, very useful information can be achieved from the results of selected cases.

The analyses will involve the modified G4(1S) guardrail placed in combination with the most commonly used types of AASHTO curbs and, additionally, the 100-mm New York curb will be included in the study matrix. Each of these curbs are shown in figure 6.1. The curb types most commonly used by the states are the AASHTO types A, B, C, D and G. Although many states do not use AASHTO curbs, most of them use curbs that are at least similar to one of the AASHTO curb types shown in figure 6.1. The AASHTO type A curb will be excluded from the curb-barrier study due to the results from the curb

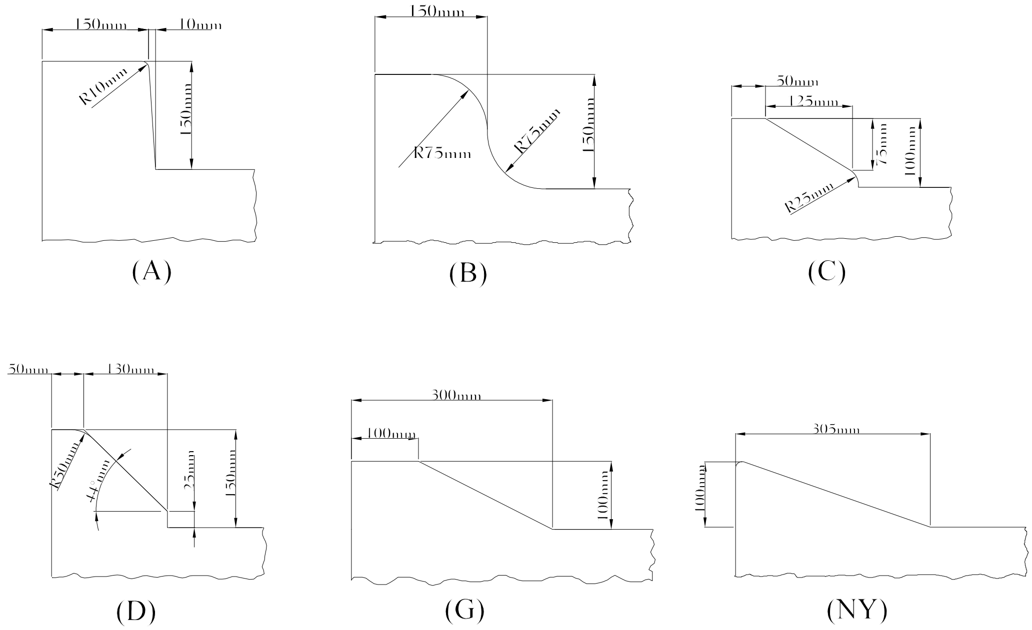

Figure 6.1: Curb types used in curb study.*(1)*

tracking study in chapter 5 in which the results of the analyses involving the AASHTO type A curb were considered inconclusive.

Three curb placement scenarios will be investigated. One scenario will involve each of the curbs placed behind the face of the barrier with the front of the curb flush with the front of the w-beam where possible. These combinations are consistent with the recommendations of the FHWA memorandum of Feb 28, 1992, and will provide useful information to the states about the performance of these currently advocated curb-barrier combinations.*(28)* Two other curb-placement scenarios will be investigated to determine the effects of curbs placed in combination with guardrails where the offset distance from curb to barrier is greater than zero, as shown below in figure 6.2. Since offset curb-barrier combinations are more common along low to moderate speed roadways (i.e., < 80 km/hr) analyses of such combinations will primarily be conducted for NCHRP Test level 2 conditions (i.e., 70-km/hr), although a select number of impacts with certain curb-barrier combinations will be investigated at higher speeds. The placement of the curbs in those analyses will be based on the results of the curb-tracking study of Chapter 5 with consideration given to the clear zone distances that are required for typical roadways.

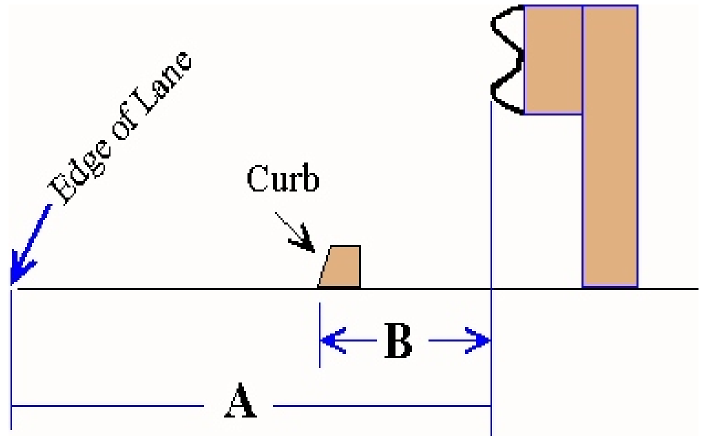

Figure 6.2: Schematic drawing to identify curb and barrier placement along roadway.

The backfill and the roadway terrain in the computer model simulations will have a zero slope. For design speeds of 70-80 km/hr the Roadside Design Guide states that the clear zone distance ranges from 3.5 m for roadways with an Average Daily Traffic (ADT) count of less than 750 vehicles per day (vpd) to 6.5 m for roadways with ADT greater than 6,000 vpd.*(2)* For design speeds of 100 km/hr the clear zone distance ranges from 5 m to 8.5 m for roadways with less than 750 ADT to roadways with greater than 6,000 ADT, respectively.

The matrix of simulations shown in Tables 6.1 through 6.3 will be used to investigate the effects of curbs placed in combination with the G4(1S) guardrail. Based on the bumper trajectory plots obtained from the curb traversal study in Chapter 5, a vehicle impact speed of 70 km/hr and angle of 25 degrees will result in the trajectory of the front bumper continuously increasing from the time of wheel contact with the curb until the front bumper reaches a lateral offset distance of approximately 4 m behind the curb. Furthermore, the bumper is higher than the top of the guardrail until the vehicle reaches a lateral distance of 5 m behind the curb. Since the median (as in middle value not roadway median) clear zone distance is approximately 5 m it would not be of interest to investigate offset distances of 5 m or greater since the guardrail would not be warranted outside the clear zone area.*(2)* In these cases offset distances of 2.5 m and 4 m will be investigated under impact conditions consistent with NCHRP Report 350 Test 2-11 (refer to table 6.1).*(20)*

For the case of the modified C2500R pickup model traversing a curb at 100 km/hr and 25 degrees the bumper trajectory plots from the curb traversal study indicate that the bumper trajectory continuously increases after wheel impact with the curb until the vehicle reaches a lateral distance of approximately 6 m behind the curb. Furthermore, the bumper remains higher than the guardrail for a lateral distance of approximately 8 m with the maximum trajectory occurring at a lateral distance between 4 - 6 m. Computer simulated impacts with curb-barrier systems at an offset distance of 4 m will be investigated under impact conditions consistent with NCHRP Report 350 Test 3-11 (refer to table 6.2). The performance of certain curb-barrier systems will also be investigated at 85 km/hr which will represents the upper speed range for intermediate speed roadways (i.e., 60-80 km/hr) (refer to table 6.3).

Table 6.1: Matrix of simulations regarding offset distance of curb to barrier for modified G4(1S) guardrail system under NCHRP **Test 2-11** impact conditions (70 km/hr).

Curb Type	Offset Distance from Barrier to Curb		
	0 m	2.5 m	4 m
B	✔	✔	✔
C	✔	✔	✔
D	✔	✔	✔
G	✔	✔	✔
NY	✔	✔	

Table 6.2: Matrix of simulations regarding offset distance of curb to barrier for modified G4(1S) guardrail system under NCHRP **Test 3-11** impact conditions (100 km/hr).

Curb Type	Offset Distance from Barrier to Curb		
	0 m	2.5 m	4 m
B	✔		✔
C	✔		✔
D	✔		
G	✔	✔	✔
NY	✔		✔

Table 6.3: Matrix of simulations regarding offset distance of curb to barrier for modified G4(1S) guardrail system at impact speed of 85 km/hr and angle of 25 degrees.

Curb Type	Offset Distance from Barrier to Curb		
	0 m	2.5 m	4 m
B	✔	✔	✔
C	✔	✔	✔

6.3 Data Collected

The information collected from the analyses is being used to determine the effectiveness of the guardrail to safely contain and redirect the vehicle during impact with the curb-barrier system. The data that were collected are listed below and are included as Appendices to this document. They include:

Appendix 8. Sequential snapshots of the impact event,

Appendix 9. Acceleration-time histories,

Appendix 10. Yaw-, pitch- and roll-time histories,

Appendix 11. W-beam tensile force-time histories, and

Appendix 12. Test Risk Assessment Program Results.

6.3.1 Sequential Snapshots of Impact Event

Sequential snapshots from the analysis are presented in a frontal view and an overhead view. These figures will provide a qualitative means of assessing vehicle stability and trajectory during and after impact, as well as apparent barrier override or underride. Each of these views are illustrated in figure 6.3.

6.3.2 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 can be determined.

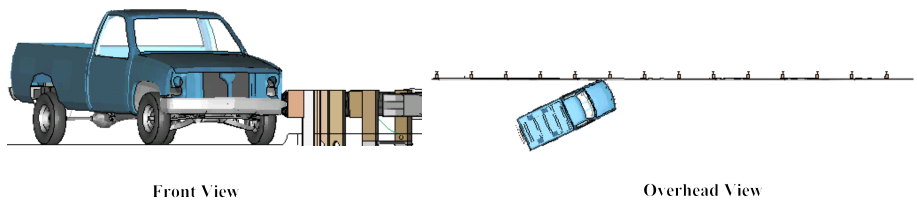

Figure 6.3: Typical view points for sequential snapshots taken from F.E. analyses.

6.3.3 Yaw-, Pitch- and Roll-Time Histories

Vehicular angular displacements (i.e., yaw, pitch and roll) will also be collected at the center of gravity of the vehicle. These data will provide vital quantitative information regarding vehicle stability during and after impact and also provide information regarding occupant risk factors. Another important issue that will be assessed using this data is vehicle yaw-position at time of impact with the guardrail system. For cases in which the guardrail is offset from the curb, the impact of the wheels of the vehicle with the curb may cause the vehicle to yaw such that the vehicle impacts the guardrail at an angle other than 25 degrees which will affect the severity of the impact.

6.3.4 Maximum Tensile Force in W-Beam Rail

An important aspect of guardrail collisions that can not accurately be simulated using the current finite element model is guardrail rupture. In a full-scale crash test that was conducted at the Midwest Roadside Safety Facility in May of 1998, a guardrail-curb combination was tested under NCHRP Report 350 test 3-11 conditions, which resulted in the guardrail rupturing at a splice connection.*(28)* Such failure can be assessed with FEA, however, the model used in the current analyses did not incorporate a failure criteria on the w-beam rail elements. This is because accurate simulation of rupture using Lagrangian finite element methods requires a refined mesh (i.e., very small elements) in the fracture region which would result in a very small time-step in order to obtain a stable solution using the explicit time-integration scheme.

Since failure conditions are typically based on failure strain, which is very sensitive to mesh density, it is common practice to exclude failure in the full-scale simulation and rely the results of the full-scale simulation to identify the critical regions in the system (e.g., post and w-beam connections) that may have a potential for failure. Sub-models of these components could then be developed in order to thoroughly assess the performance of those components. This method, however, would severely limit the number of curb-barrier impact scenarios that could be investigated.

Another means of assessing the potential for guardrail rupture is to examine tensile forces in the w-beam during collision. Guardrail rupture is often associated with relatively large displacement of the anchor system which leads to "pocketing". Pocketing is a term used to describe a situation in which there is large lateral displacement of the rail concurrent with a decrease in guardrail tension downstream of the vehicle which causes the rail element to form a pocket shape between two adjacent posts, thereby impeding the vehicle's redirection back out of the system. In such cases the rail element will likely rupture either downstream of the vehicle at a post location where there is a high curvature of the rail (e.g., high bending stresses) or at a splice connection just upstream of the vehicle where there is an increase in rail tension.*(28)* In extreme cases of pocketing the guardrail may experience very low tensile forces or even compression downstream of the vehicle while the upstream sections of rail experience very large tensile forces.

The tensile forces in the rail were collected at four locations along the guardrail, as shown schematically in figure 6.4 and identified below:

A. the nearest splice connection downstream of the impact point,
B. the nearest splice connection upstream of the impact point,
C. the upstream anchor and
D. at a downstream location outside the impact zone.

The results for each of the curb-guardrail analyses were compared to the results of the

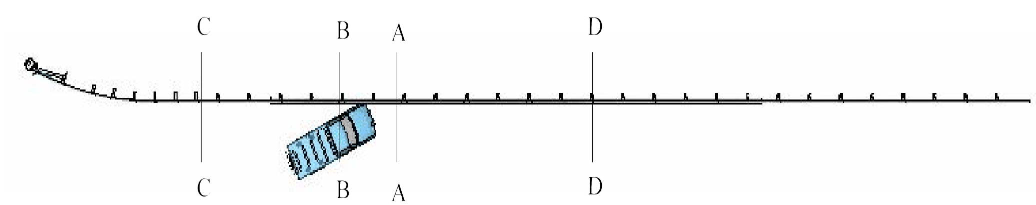

Figure 6.4: Schematic view of the finite element model identifying the locations at which cross-section force data in the w-beam rail was collected.

guardrail analyses without a curb present. Previous results from finite element analysis and crash tests on the modified G4(1S) without a curb imply that the forces in the guardrail under NCHRP Report 350 test 3-11 impact conditions are close to the maximum capacity that the guardrail can withstand without rupture or without causing excessive anchor movement.*(56)* If the rail forces are significantly higher in the curb-guardrail simulations than they are in the simulations without a curb present, then there may be a potential for rupture in those cases.

6.3.5 Test Risk Assessment Program (TRAP) Results

The acceleration data and displacement-time history data discussed above will be used in the Test Risk Assessment Program (TRAP).*(46)* NCHRP Report 350 requires that the occupant impact velocity (OIV) in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration (ORA) (i.e., the maximum vehicle acceleration averaged over 10 ms interval after occupant impact) in the longitudinal direction should not exceed 20 G's. Both the NCHRP occupant risk factors and the CEN risk factors will be reported, however, the CEN data are not required by the Federal Highway Administration and will not be considered in the performance evaluation of the curb-barrier systems.

6.4 Results

At the beginning of each analysis the vehicle was aligned to impact post 14 of the guardrail system. This point is 2.4 m upstream of a splice connection. The exact impact point may vary in some cases where the barrier is offset from the curb depending on the yaw angle of the vehicle after impact with the curb. 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-Guardrail_AVIS/** . Summary tables and graphs of the results of the study are presented below.

6.4.1 Sequential Snapshots of the Impact Event

Sequential snapshots of the impact event are shown in Appendix 8. These images provide a qualitative means of evaluating the general behavior of vehicle interaction with the guardrail as well as the important safety issues regarding vehicle kinematics such as barrier override, barrier underride, vehicle overturn, and vehicle redirection. Table 6.4 summarizes the results based upon the images in Appendix 8. It is important to note that vehicle impact into roadside barriers is highly nonlinear which means that small variations in the system may lead to different results. Such variations may include impact conditions, impact location on the barrier, vehicle suspension properties, soil conditions, barrier connections, and barrier component properties to name only a few. Because of the nature of these factors the results of the finite element analyses should only be viewed as a tool for assessing the performance of the system, and are thus only representative of a possible outcome for the conditions specified.

Table 6.4: Summary of results from images of sequential snapshot data regarding vehicle override, underride, rollover and redirection.

Offset Distance	Impact Speed	Curb Type	Over-ride	Under-ride	Roll-over	Redirection Comments
0.0 m	70 km/hr	B	-	-	-	Stable redirection
		C	-	-	-	Stable redirection
		D	-	-	-	Slight bumper trajectory, Stable redirection
		G	Analysis Not Conducted			
		NY	-	-	-	Stable redirection
	85 km/hr	B	-	-	-	Slight pitch
		C	-	-	-	Stable redirection
	100 km/hr	B	-	-	Possible	Excessive pitch
		C	Likely	-	Likely	Excessive trajectory
		D	-	-	Possible	Excessive pitch
		G	-	-	Possible	Excessive pitch
		NY	-	-	-	Moderate pitch, stable redirection
2.5 m	70 km/hr	B	-	-	-	Moderate roll angle, high yaw rate, bumper gets above rail
		C	-	-	-	Moderate roll angle, high yaw rate, slight bumper trajectory
		D	-	-	-	Moderate roll angle, high yaw rate, bumper gets above rail, tierod breaks
		G	-	-	-	Moderate roll angle, high yaw rate, Bumper gets above rail
		NY	-	-	-	Stable redirection, high yaw rate
	85 km/hr	B	Likely The analysis terminated prematurely as the bumper started over the rail.	-	-	Excessive roll angle, bumper gets over rail
		C	Likely The analysis terminated prematurely as the bumper started over the rail.	-	-	Excessive roll angle, bumper gets over rail

Table 6.4: (CONTINUED) Summary of results from images of sequential snapshot data regarding vehicle override, underride, rollover and redirection.

Offset Distance	**Impact Speed**	**Curb Type**	**Over-ride**	**Under-ride**	**Roll-over**	**Redirection Comments**
2.5 m	**100 km/hr**	G	Likely	-	Likely	Bumper gets over rail, truck rolls over
4.0 m	**70 km/hr**	B	-	-	-	Analysis terminated during redirection
		C	-	-	-	Stable redirection
		D	-	-	-	Stable redirection
		G	-	-	-	
		NY	Analysis Not Conducted			
	85 km/hr	B	-	-	-	Stable redirection, high yaw rate
		C	-	-	-	Stable redirection, high yaw rate
	100 km/hr	B	Likely	-	-	override
		C	Likely	-	-	override
		D	Analysis Not Conducted			
		G	Likely	-	-	override
		NY	Possible	-	-	Excessive trajectory
			Analysis terminated prematurely during redirection			

For example, in many cases the trajectory of the vehicle during interaction with the barrier causes the tires to impact higher than normal against the w-beam rail. With the wheels in this position the connection of the w-beam to the post becomes a critical factor. If the connection between the w-beam and post does not fail quickly enough during impact, the posts may pull the w-beam down to a point that allows the wheels of the vehicle to ride up the rail and launch the vehicle, as was the case involving the simulation of the modified C2500R impacting an AASHTO C curb at 100 km/hr and 25 degrees with the guardrail positioned at 0-m offset from the curb. Figure 6.5 shows the results of the simulation at a specific time during the impact. A more complete illustration of the impact event is provided in Appendix H.

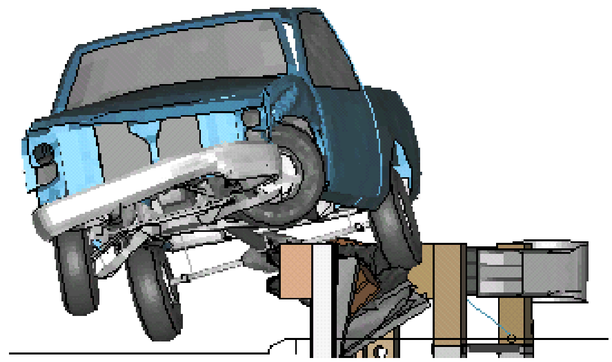

Figure 6.5: F.E. simulation of 2000-kg pickup impacting guardrail with AASHTO type C curb underneath rail.

A similar event also occurred in a recent crash test performed at the Midwest Roadside Safety Facility in Lincoln, Nebraska which was documented in a test report by Polivka et al.*(29)* That test involved a modified G4(1S) guardrail with a 102-mm curb placed underneath the rail behind the face of the w-beam under impact conditions corresponding to NCHRP Report 350 Test 3-11. A section of the guardrail in the impact region incorporated two layers of w-beam (e.g., nested w-beams) to reduce the potential for rupture. Consequently, this resulted in four layers of w-beam at the splice connections and required a much higher force to pull the head of the bolt through w-beam slots in the connection of the rail to the posts. As a result of the stronger connection the w-beam rail was pulled down and the vehicle launched into the air, as shown in Figure 6.6 (figure 6.6 was taken from polivka et al *(29)*). Although the vehicle experienced extreme trajectory during the impact, the vehicle remained upright and came down on the front side of the guardrail and satisfied all requirements of NCHRP Report 350. The repeatability of such an event is questionable due to the instability of the vehicle during impact with the system, thus slight changes in either the system or impact conditions may lead to drastically different results.

Impact Speed of 70 km/hr and Angle of 25 Degrees - Based on the sequential views of the simulated impact events in which the barrier is positioned at 0-m offset from the curb it appears that for impact speeds of 70 km/hr and impact angle of 25 degrees the vehicle remains very stable throughout the impact event and barrier damage appears to be minimal, regardless of curb type. The scenario with the 150-mm AASHTO type D curb, however, resulted in the bumper getting above the rail during redirection but the potential for override of the barrier appears minimal.

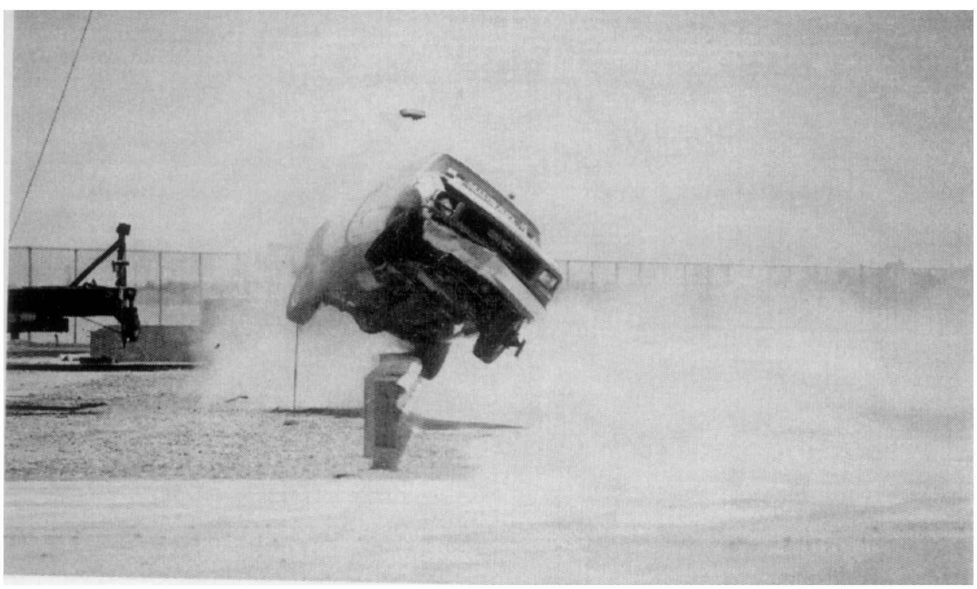

Figure 6.6: NCHRP Report 350 Test 3-11 impact with modified G4(1S) guardrail with nested 12-gauge w-beams and a 102-mm curb under the rail. *(29)*

For the cases involving the barrier positioned at 2.5-m offset from AASHTO curb types B, C, D and G, the sequential views of the impact events suggests that the vehicle will experience moderate roll angle during impact and a relatively high yaw rate (e.g., the front of vehicle redirects out of the system before the rear of the vehicle contacts the rail). Also, for the cases involving 150-mm curb types the bumper of the vehicle gets above the rail but there is little possibility of override in those cases. The impact scenario involving the 100-mm New York curb resulted in very stable redirection, however, the yaw rate appeared somewhat high in this case as well.

For the cases involving the barrier positioned at 4.0-m offset from the curbs the vehicle remains very stable throughout the impact event and barrier damage appears to be minimal, regardless of the type of curb used in conjunction with the guardrail. However, the vehicle appears to experience a high yaw rate during redirection which may increase risk of occupant injury.

<u>Impact Speed of 85 km/hr and Angle of 25 Degrees</u> - Only two curb types, the 150-mm AASHTO type B and the 100-mm AASHTO type C curbs, were used in the curb-barrier scenarios involving impact speed of 85 km/hr and impact angle of 25 degrees. These cases were analyzed in order to assess the performance of the curb-barrier systems at speeds corresponding to the upper bound of the moderate-speed range (i.e., 60-80 km/hr) and the lower bound of the high-speed range (i.e., > 80 m/hr).

For the cases involving the barrier positioned at 0.0-m offset from the curbs the sequential views of the impact suggests that the vehicle will remain relatively stable during impact. There was a slight pitch of the vehicle when the rear wheels contacted the 150-mm AASHTO type B curb. For the cases with the barrier positioned at 2.5-m offset from the curb the analyses terminated prematurely due to numerical problems in the calculations which were related to contact between the w-beam rail and truck fender. The analyses did continue long enough, however, to conclude that there is a potential for excessive roll of the vehicle during impact and that the bumper is likely to get over the w-beam rail. Furthermore, the momentum of the truck combined with the excessive trajectory of the bumper is sufficient to cause barrier override. For the cases involving the barrier positioned at 4.0-m offset from the curb the sequential views of the impact events suggests that the vehicle will remain stable but it is likely to experience a high yaw rate during redirection.

<u>Impact Speed of 100 km/hr and Angle of 25 Degrees</u> - The sequential views of the impact events involving the barrier positioned at 0.0-m offset from the curbs indicate that rollover of the vehicle is possible for each curb-barrier scenario involving the AASHTO types B, C, D and G curbs due to excessive pitch of the vehicle during redirection. Although the vehicle did not rollover in the simulations, the amount of damage to the front impact side wheel during impact and the position of the front wheels during redirection become a critical factor regarding vehicle stability when the pitch angle of the vehicle is excessive during redirection. In the simulations the wheels remained

undamaged and in straight alignment during redirection. There was one case of barrier override involving the 100-mm AASHTO type C curb. In this analysis a wheel snag against a guardrail blockout early in the impact event caused the tierod to break. The front wheel on the impact side of the vehicle then rotated 90 degrees toward the guardrail. The w-beam rail was pushed down and the vehicle launched over the guardrail.

The impact scenario involving the 100-mm New York curb resulted in minimal trajectory of the vehicle with only moderate pitch and a relatively stable redirection.

Only one curb type, the AASHTO type G curb, was used in the case involving the barrier positioned at 2.5-m offset from the curb. The trajectory of the truck was excessive during impact and, although the trajectory of the front bumper and the momentum of the vehicle appeared sufficient to cause the vehicle to override the barrier, the guardrail redirected the vehicle away from the system where it then proceeded to roll over onto its side. For the cases involving the barrier positioned at 4.0-m offset from the curb the sequential views of the impact events suggest that barrier override is likely regardless of curb type. Note: the analysis involving the 100-mm New York curb resulted in premature termination due to numerical problems in the calculations which were related to contact between the front tire and the w-beam, however, at the time the analysis was stopped the trajectory and roll angle of the truck was excessive enough to suspect barrier override and/or rollover.

6.4.2 Angular Displacement-Time History Data

The roll, pitch and yaw angle displacement-time history data was collected at the center of gravity of the vehicle during the impact event and are shown graphically in Appendix 10. Table 6.5 gives a summary of the vehicle angular position at the time of impact with the guardrail, the maximum roll and pitch angle of the vehicle during the impact event and the yaw angle of the vehicle as it exits guardrail. Figures 6.7, 6.8 and 6.9 illustrate graphically the initial angular positions of the vehicle at time of impact with guardrail and figures 6.10 and 6.11 show maximum roll angle and maximum pitch angle for each of the curb-barrier impact scenarios, respectively.

Figure 6.7 and 6.8 indicate that when the barrier is offset a distance of 2.5 m from the curb and the truck impacts the system at speeds of 70 km/hr and 85 km/hr the initial roll and pitch angle of the vehicle at time of impact with the guardrail are typically both positive (refer to local coordinate system of figure 5.4) with the exception of the 100-mm New York curb. This results in the position of the front bumper on the impact side of the vehicle being higher than normal at the time of impact and, according to a qualitative analysis of the sequential views of the impact, the bumper was above the rail during impact for each of these cases. The maximum roll angle of the vehicle during impact was relatively higher in those cases as well, as shown in figure 6.10. The graph corresponding to impact speed of 85 km/hr is a little misleading since the vehicle overrode the barrier in those cases and the analysis was terminated before maximum roll was achieved.

Table 6.5: Summary of results from angular displacement-time history data collected at the center of gravity of the vehicle in the analyses.

Offset Distance	Impact Speed	Curb Type	Impact Angle with Guardrail (degrees)			Maximum Angular Displacements During Impact (degrees)		
			Roll	Pitch	Yaw	Roll	Pitch	Yaw
0.0 m	70 km/hr	B	0.0	0.0	-25.0	-1.9	-6.4	21.0
		C	0.0	0.0	-25.0	-7.0	-3.7	21.0
		D	0.0	0.0	-25.0	2.2	3.5	20.2
		G	Analysis not conducted					
		NY	0.0	0.0	-25.0	-4.3	-2.1	21.3
	85 km/hr	B	0.0	0.0	-25.0	5.4	-7.6	19.3
		C	0.0	0.0	-25.0	8.2	-3.3	18.5
	100 km/hr	B	0.0	0.0	-25.0	-18	-14.2	22.4
		C	0.0	0.0	-25.0	31.3	6.0	29.5
		D	0.0	0.0	-25.0	-12.5	-14.3	24.2
		G	0.0	0.0	-25.0	-11.4	-21.6	23.0
		NY	0.0	0.0	-25.0	-10.9	-9.1	23.5
2.5 m	70 km/hr	B	0.27	0.44	-25.8	-11.9	-3.2	13.7
		C	Data wasn't recorded due to input error					
		D	0.89	1.13	-26.8	-11.4	-5.2	18.9
		G	3.48	0.16	-26.2	-14.1	-6.3	19.9
		NY	2.87	-0.17	-26.0	-8.4	-5.2	15.8
	85 km/hr	B	1.22	1.33	-25.7	-	-	-
		C	2.92	0.55	-26.3	-	-	-
4.0 m	70 km/hr	B	-1.95	-1.14	-28.8	5.1	-2.8	NA
		C	-3.39	-2.48	-28.0	-7.6	-2.7	17.7
		D	-1.80	-1.55	-29.7	5.6	-2.9	19.2
		G	0.49	-0.85	-26.8	4.4	-3.4	14.6
		NY	Analysis not conducted					
	85 km/hr	B	-1.63	-0.81	-27.8	-10.8	-2.0	18.9
		C	-0.82	-1.78	-28.1	-6.3	-3.2	17.0
	100 km/hr	B	0.0	-0.49	-28.7	-19.6	-6.2	NA
		C	-0.06	-1.42	-27.6	-6.7	-3.5	NA
		G	2.21	-0.93	-27.5	-45.1	3.5	NA
		NY	1.84	-0.95	-27.5	-15.2	-3.1	NA

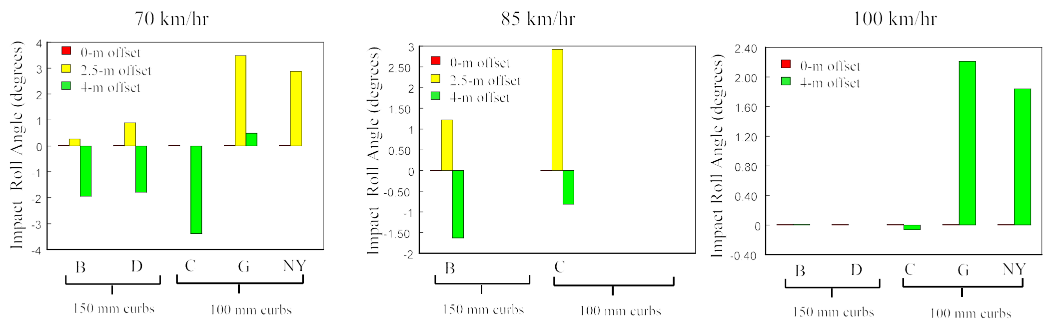

Figure 6.7: Initial roll angle of the vehicle at time of impact with guardrail.

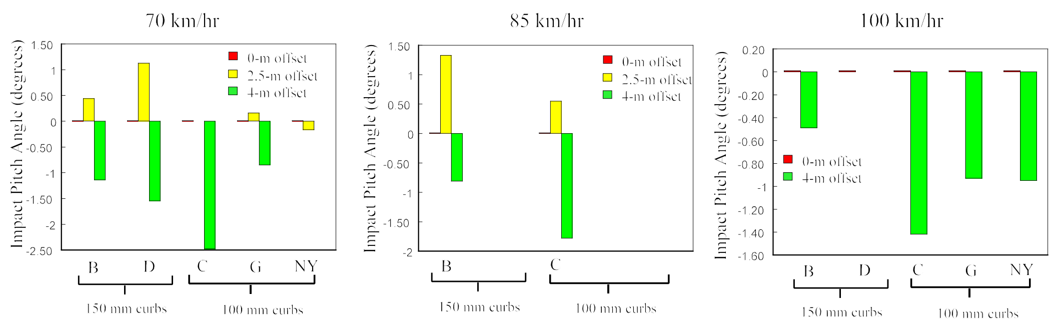

Figure 6.8: Initial pitch angle of the vehicle at time of impact with guardrail.

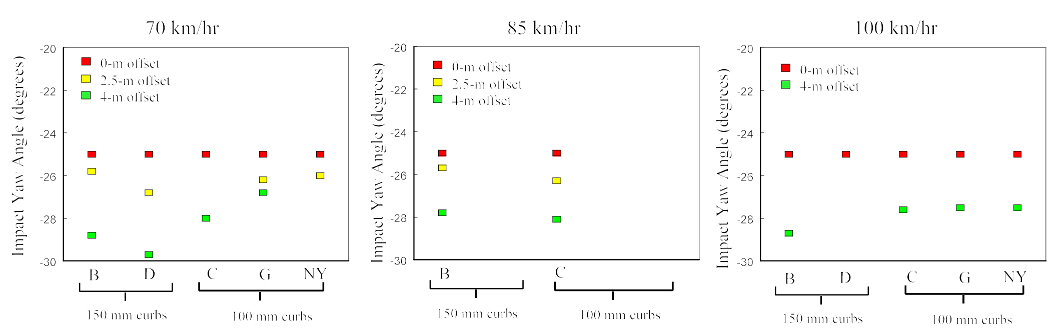

Figure 6.9: Initial yaw angle of the vehicle at time of impact with guardrail.

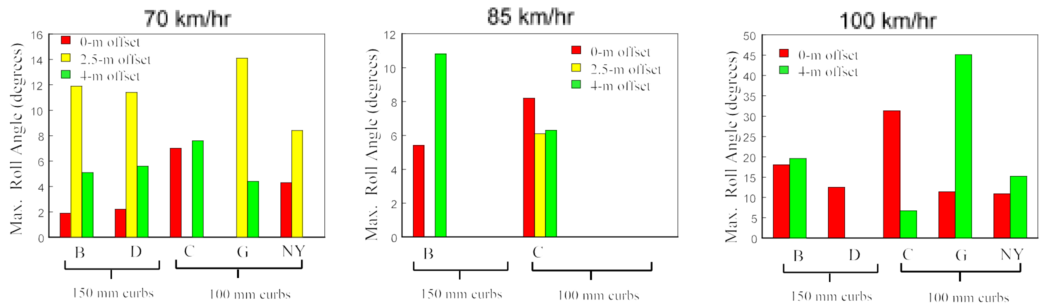

Figure 6.10: Maximum roll angle measured at the center of gravity of the pickup truck model during curb-barrier impact.

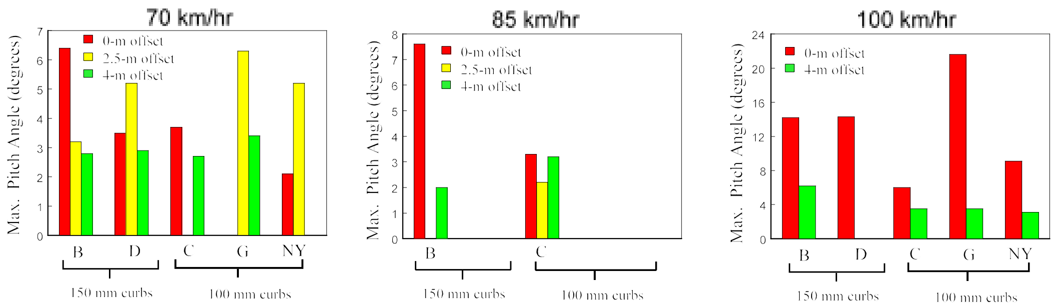

Figure 6.11: Maximum pitch angle measured at the center of gravity of the pickup truck model during curb-barrier impact.

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The cases involving the barrier offset a distance of 4.0 m from the curb and impact speeds of 70 km/hr and 85 km/hr, the opposite was typically true, with both the initial roll and pitch angle of the vehicle being negative at time of impact with the guardrail. In those cases the position of the front bumper on the impact side was relatively lower and, according to the sequential views, the bumper stayed below the top of the rail throughout the impact event. For the scenarios involving impact speeds of 100 km/hr the initial roll angle was typically either zero or positive while the initial pitch angle was typically negative. In those cases the trajectory and momentum of the vehicle dominated and the primary result was vehicle override as illustrated in the sequential views. The graph of maximum roll angle of the vehicle in figure 6.10 is misleading regarding the 4-m offset scenarios since the analysis was terminated prematurely in each of those cases as the vehicle began to override the barrier.

In all cases involving the barrier offset at distances of 2.5 m or 4.0 m from the curb, the curb caused the wheels of the truck to steer toward the guardrail as the vehicle traversed the curb and resulted in the vehicle impacting the guardrail at a steeper than normal angle, as shown in figure 6.9. Consequently, for any given curb-barrier case the impact angle gets steeper as the offset distance increases. A steeper impact angle may increase the severity of the impact by increasing the potential for failure of the barrier and by increasing occupant risk factors.

6.4.3 Tensile Force in W-Beam

The tensile force-time history plots of the w-beam cross-section at two critical locations (e.g., in the impact region of the guardrail and at the upstream anchor) as computed in the finite element analyses are provided in Appendix 11. Table 6.6 provides a summary of the maximum values of tensile force at those locations and the results are also illustrated graphically in figures 6.12 - 6.18. The cases involving the modified C2500R pickup model impacting the guardrail at100 km/hr and 25 degrees with an offset distance of 0.0 m from curb to barrier are compared to the results of the modified C2500R pickup model impacting the guardrail under the same impact conditions without a curb present. If the rail forces are significantly higher in the curb-guardrail simulations than they are in the simulations without a curb present then there may be a potential for rupture in those cases.

From the results of the finite element simulation of the guardrail without a curb present under NCHRP Report 350 test 3-11, the maximum force in the guardrail occurs in the impact region and is 209 kN and the maximum anchor force is approximately 179 kN.

<u>Impact Speed of 70 km/hr and Angle of 25 Degrees</u> **-** The results from the analyses of vehicle impact with the guardrail under Test 2-11 conditions involving each of the different curb types indicate that rupture of the guardrail is not likely to occur regardless of the offset location of the barrier with respect to the curb, as shown in table 6.6 and figures 6.12, 6.13 and 6.14.

For the cases involving the guardrail positioned at 0.0-m offset from the curb the maximum tension in the w-beam rail ranged from 61 to 65 percent and the maximum force at the upstream anchor ranged between 69 and 71 percent of the values computed in the analysis of the guardrail without a curb present under Test 3-11 impact conditions. For the cases involving the guardrail positioned at 2.5-m offset from the curb the

Table 6.6: Summary of maximum tensile force values in the w-beam rail within the impact region and at the upstream anchor.

Offset Distance	Impact Speed	Curb Type	Maximum Tensile Force in W-Beam Rail					
			Impact Region		Upstream Anchor		Downstream Location	
			(kN)	Force/ 209	(kN)	Force/ 179	(kN)	Force/ 147
0.0 m	70 km/hr	B	127	0.61	-	-	71.2	0.48
		C	127	0.61	124	0.69	87.8	0.60
		D	128	0.61	127	0.71	82.9	0.56
		G	Analysis not conducted					
		NY	135	0.65	131	0.73	76.0	0.52
	85 km/hr	B	165	0.79	141	0.79	117	0.80
		C	170	0.81	142	0.79	122	0.83
	100 km/hr	B	232	1.11	-	-	182	1.24
		C	226	1.08	202	1.13	175	1.19
		D	243	1.16	210	1.17	183	1.24
		G	223	1.07	-	-	174	1.18
		NY	231	1.11	198	1.11	178	1.21
2.5 m	70 km/hr	B	95.0	0.45	88.7	0.50	68.6	0.47
		C	Data wasn't recorded due to input error					
		D	128	0.61	120	0.67	82.1	0.56
		G	123	0.59	118	0.66	77.8	0.53
		NY	132	0.63	119	0.66	77.7	0.53
	85 km/hr	B	185	0.89	-	-	91.0	0.62
		C	205	0.98	177	0.99	102	0.69
4.0 m	70 km/hr	B	101	0.48	89.4	0.50	66.1	0.45
		C	114	0.55	113	0.63	76.5	0.52
		D	97.5	0.47	-	-	65.1	0.44
		G	130	0.62	116	0.65	78.8	0.54
		NY	Analysis not conducted					
	85 km/hr	B	171	0.82	143	0.80	103	0.70
		C	171	0.82	148	0.83	120	0.82

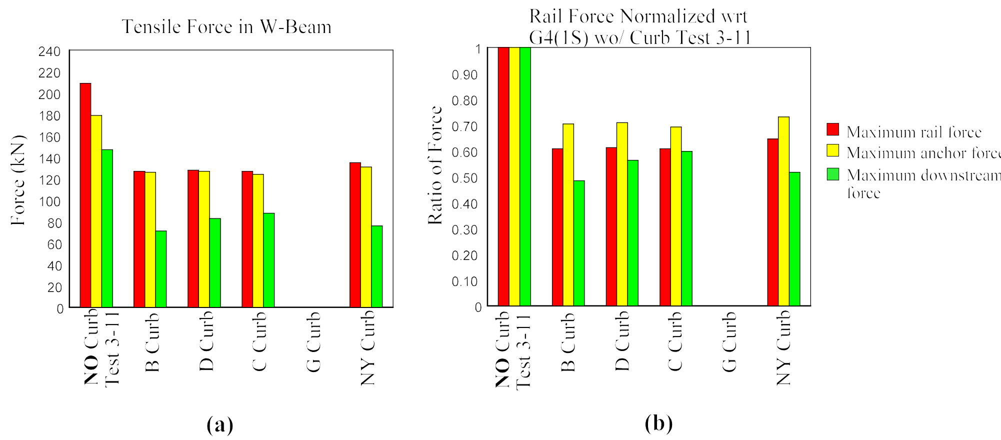


Figure 6.12: Maximum w-beam rail force in impact region of guardrail and at the upstream anchor for the cases involving C2500 impact at **70 km/hr** and 25 degrees with curb at **0-m offset**.(a) Maximum tensile force in w-beam and (b) Maximum tensile force in w-beam normalized wrt the force in w-beam under NCHRP Report 350 Test 3-11 impact conditions when curb is not present.

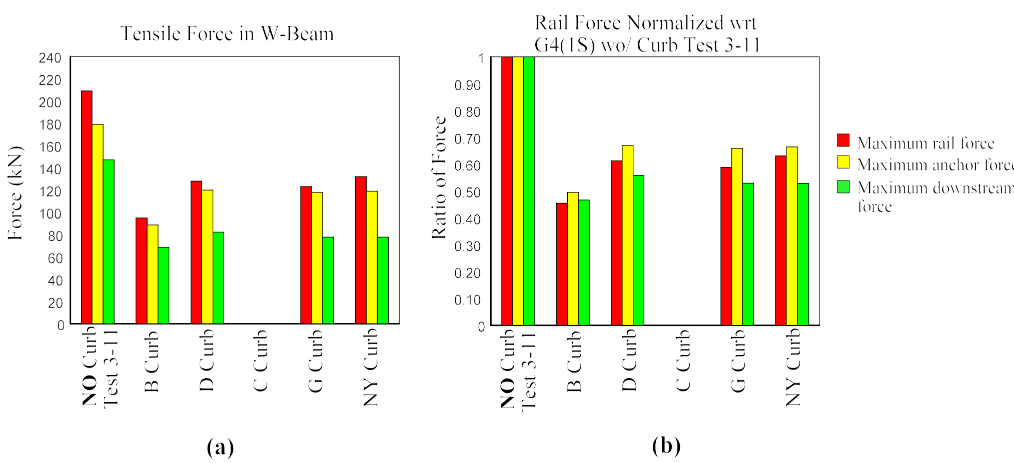


Figure 6.13: Maximum w-beam rail force in impact region of guardrail and at the upstream anchor for the cases involving C2500 impact at **70 km/hr** and 25 degrees with curb at **2.5-m offset**.(a) Maximum tensile force in w-beam and (b) Maximum tensile force in w-beam normalized wrt the force in w-beam under NCHRP Report 350 Test 3-11 impact conditions when curb is not present.

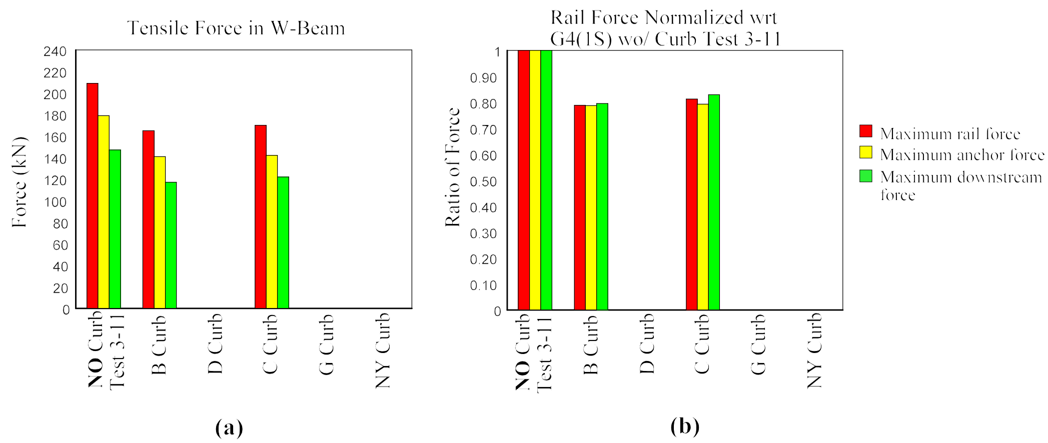


Figure 6.14: Maximum w-beam rail force in impact region of guardrail and at the upstream anchor for the cases involving C2500 impact at **85 km/hr** and 25 degrees with curb at **0.0-m offset**.(a) Maximum tensile force in w-beam and (b) Maximum tensile force in w-beam normalized wrt the force in w-beam under NCHRP Report 350 Test 3-11 impact conditions when curb is not present.

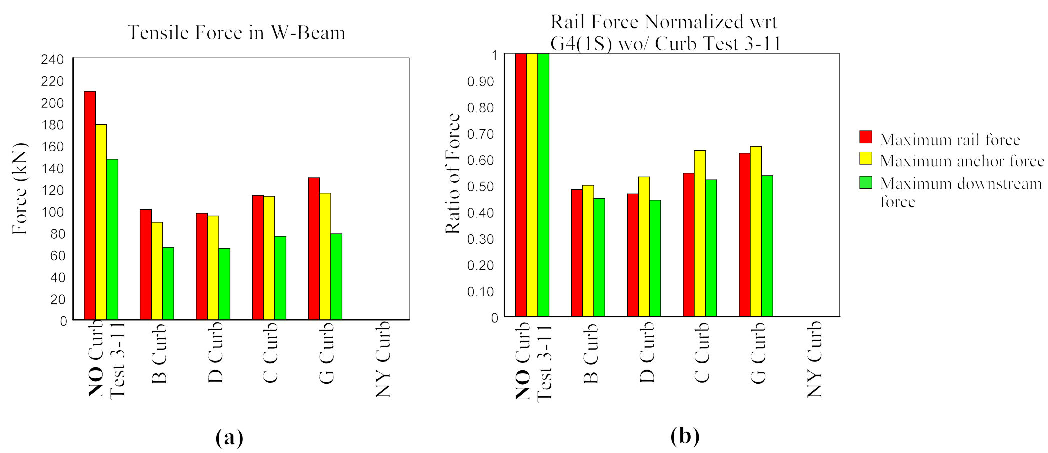
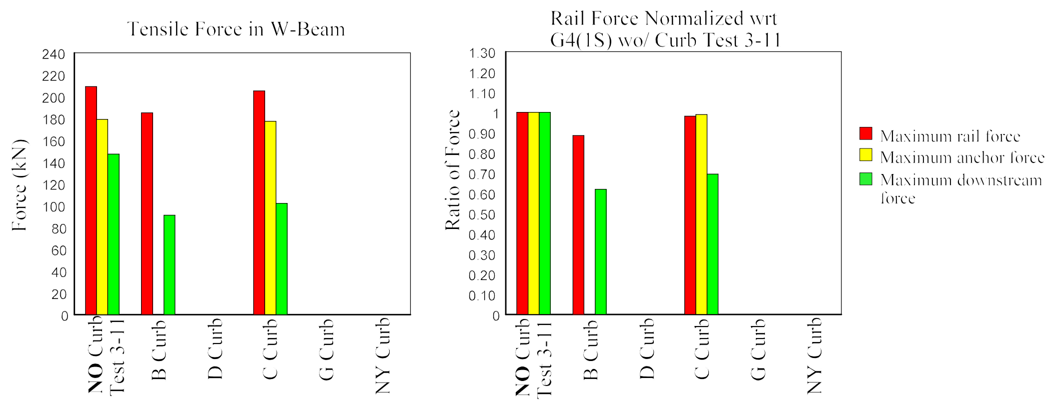
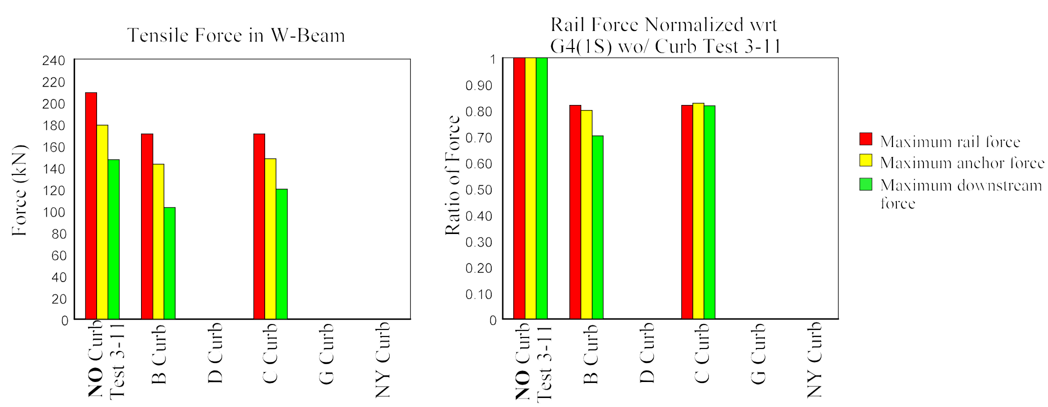


Figure 6.15: Maximum w-beam rail force in impact region of guardrail and at the upstream anchor for the cases involving C2500 impact at **70 km/hr** and 25 degrees with curb at **4.0-m offset**.(a) Maximum tensile force in w-beam and (b) Maximum tensile force in w-beam normalized wrt the force in w-beam under NCHRP Report 350 Test 3-11 impact conditions when curb is not present.



(a) (b)

Figure 6.16: Maximum w-beam rail force in impact region of guardrail and at the upstream anchor for the cases involving C2500 impact at **85 km/hr** and 25 degrees with curb at **2.5-m offset**.(a) Maximum tensile force in w-beam and (b) Maximum tensile force in w-beam normalized wrt the force in w-beam under NCHRP Report 350 Test 3-11 impact conditions when curb is not present.



(a) (b)

Figure 6.17: Maximum w-beam rail force in impact region of guardrail and at the upstream anchor for the cases involving C2500 impact at **85 km/hr** and 25 degrees with curb at **4.0-m offset**.(a) Maximum tensile force in w-beam and (b) Maximum tensile force in w-beam normalized wrt the force in w-beam under NCHRP Report 350 Test 3-11 impact conditions when curb is not present.

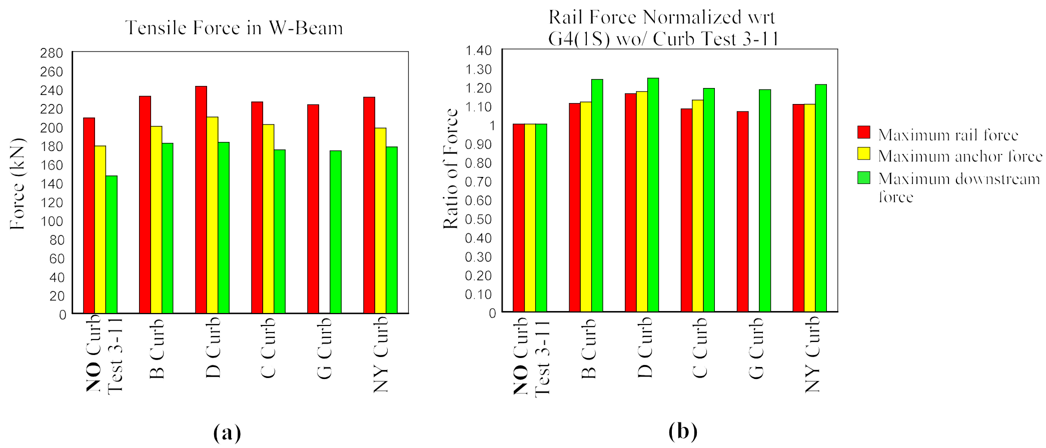


Figure 6.18: Maximum w-beam rail force in impact region of guardrail and at the upstream anchor for the cases involving C2500 impact at **100 km/hr** and 25 degrees with curb at **0-m offset**.(a) Maximum tensile force in w-beam and (b) Maximum tensile force in w-beam normalized wrt the force in w-beam under NCHRP Report 350 Test 3-11 impact conditions when curb is not present.

maximum tension in the w-beam ranged from 45 to 63 percent and the maximum force at the upstream anchor ranged between 50 and 67 percent of the values computed in the analysis of the guardrail without a curb present under Test 3-11 impact conditions. For the cases involving the guardrail positioned at 4.0-m offset from the curb the maximum tension in the w-beam ranged from 48 to 62 percent and the maximum force at the upstream anchor ranged between 50 and 65 percent of the values computed in the analysis of the guardrail without a curb present under Test 3-11 impact conditions.

<ins>Impact Speed of 85 km/hr and Angle of 25 Degrees</ins> - The results from the analyses of vehicle impact at 85 km/hr at 25 degrees into the guardrail with each of the different curb

types indicate that rupture of the guardrail is not likely to occur for offset distances of 0 m and 4 m, as shown in table 6.6 and figures 6.15, 6.16 and 6.17. In the cases in which the guardrail is placed 2.5 m behind the curb the tension in the rail reaches magnitudes that may be considered critical, however, in those cases there was also bumper override.

For the cases involving the guardrail positioned at 0.0-m offset from the curb the maximum tension in the w-beam rail ranged from 79 to 81 percent and the maximum force at the upstream anchor was 79 percent of the values computed in the analysis of the guardrail without a curb present under Test 3-11 impact conditions. For the cases involving the guardrail positioned at 2.5-m offset from the curb the maximum tension in the w-beam ranged from 89 to 98 percent of the values computed in the analysis of the guardrail without a curb present under Test 3-11 impact conditions. For the cases involving the guardrail positioned at 4.0-m offset from the curb the maximum tension in the w-beam was 82 percent and the maximum force at the upstream anchor ranged between 80 and 83 percent of the values computed in the analysis of the guardrail without a curb present under Test 3-11 impact conditions.

Impact Speed of 100 km/hr and Angle of 25 Degrees - The analyses of vehicle impact with the guardrail under Test 3-11 conditions involving each of the different curb types located at 0-m offset (i.e., under the w-beam rail) resulted in significantly higher forces in the rail and anchor compared to the case of the guardrail without a curb present, as shown in table 6.6 and figure 6.18. In all cases, however, there appears to be a potential for excessive anchor movement and rail rupture during impact. The maximum rail forces under test 3-11 conditions for curb-barrier offset distances of greater than 0.0 m are not shown since the predominate outcome in all those cases was barrier override.

For the cases involving the guardrail positioned at 0.0-m offset from the curb the maximum tension in the w-beam rail ranged from 107 to 111 percent and the maximum force at the upstream anchor was as high as 117 percent of the values computed in the analysis of the guardrail without a curb present under Test 3-11 impact conditions.

6.4.4 TRAP Results

The results from the TRAP program for each of the curb-and-barrier impact scenarios are provided in Appendix 12. Table 6.7 gives a summary of the TRAP results regarding the OIV, ORA and maximum 50 ms moving average acceleration. Figures 6.19 and 6.20 illustrate graphically a comparison of the longitudinal ORA and maximum 50 ms average longitudinal acceleration for each of the curb-barrier impact scenarios, respectively.

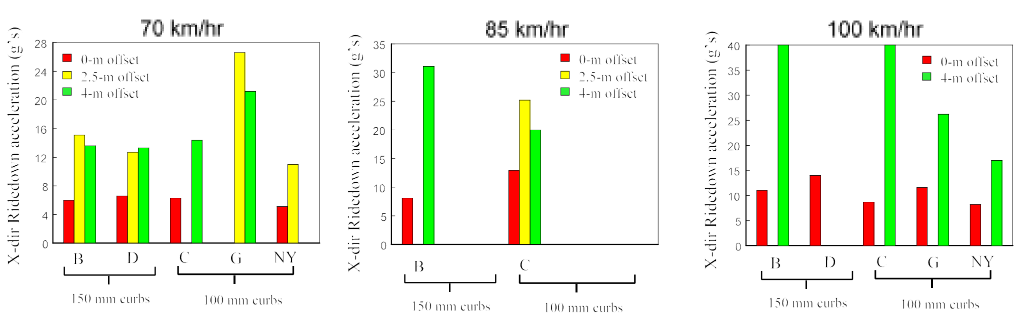


Figure 6.19: Maximum longitudinal ridedown acceleration at the center of gravity of the pickup truck model during curb-barrier impact.

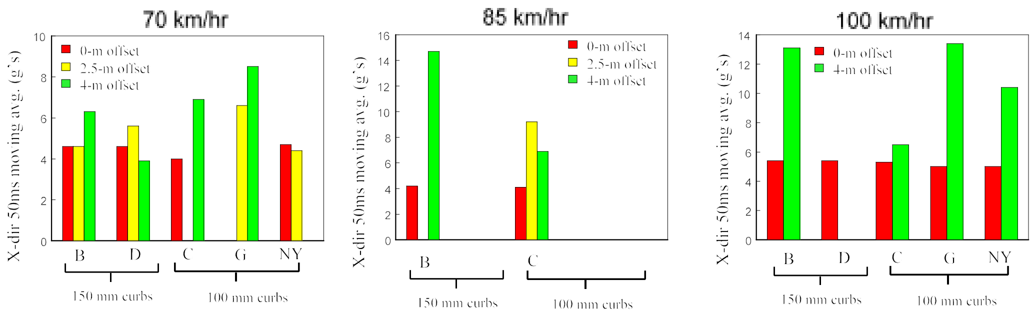


Figure 6.20: Maximum 50 ms average longitudinal acceleration at the center of gravity of the pickup truck model during curb-barrier impact.

The OIV for all cases was below the maximum limit of 12 m/s as required in NCHRP Report 350. For the curb-and-barrier scenarios in which the barrier was offset at 2.5 m and 4.0 m from the curb, the start of the data analysis began at first tire contact with the curb. In some of these cases occupant impact occurred prior to vehicle impact with the barrier (e.g., AASHTO type D curb, 70 km/hr impact speed, 2.5-m offset) which resulted in very low values of occupant impact velocity.

The longitudinal ORA values were below the maximum limit of 20 G’s required in NCHRP Report 350 for the cases of 0.0-m offset distance from curb to barrier at all three impact speeds. In the cases for which the offset distance was greater than zero, six of those resulted in longitudinal ORA values exceeding 20 G’s. Those cases are listed below:

- 150-mm AASHTO type B curb, impact speed of 85 km/hr and offset distance of 4.0 m

Table 6.7: Summary of occupant risk factors computed using the computer software TRAP and the results from the finite element analyses of the curb-and-barrier impact study.

	Curb Type	Impact Conditions		Occupant Impact Velocity (OIV)		Occupant Ridedown Accelerations (ORA)		Max. 50ms Moving Average (g's)		
		Speed (km/hr)	Offset Distance (m)	x-dir (m/s)	y-dir (m/s)	x-dir (g's)	y-dir (g's)	x-dir (g's)	y-dir (g's)	z-dir (g's)
150 mm Curbs	B	70	0.0	4.1	-3.6	-6.0	4.7	-4.6	3.3	2.0
			2.5	3.5	-2.5	-15.1	19.4	4.6	-10.0	7.4
			4.0	2.0	-4.5	13.6	-19.2	-6.3	8.3	-6.7
		85	0.0	4.2	-4.1	8.1	10.6	-4.2	5.7	4.2
			2.5	-	-	-	-	-	-	-
			4.0	0.1	-2.6	31.1	29.0	-14.7	10.1	-9.0
		100	0.0	5.5	-5.0	-11.0	14.9	-5.4	7.6	3.3
			4.0	3.6	0.3	-40.0	-49.9	-13.1	9.6	-14.6
	D	70	0.0	4.3	-4.1	-6.6	6.7	-4.6	3.7	-2.0
			2.5	-0.1	1.6	-12.7	17.3	-5.6	5.8	-7.7
			4.0	0.3	-1.6	13.3	14.4	-3.9	7.2	5.1
		100	0.0	5.9	-4.8	-14.0	15.9	-5.4	7.1	3.5
	C	70	0.0	4.2	-4.2	-6.3	7.5	-4.0	3.8	-1.7
			2.5	-	-	-	-	-	-	-
			4.0	1.6	1.4	14.4	13.8	6.9	6.3	6.8
		85	0.0	4.1	-4.3	-12.9	12.6	-4.1	5.5	2.3
			2.5	6.1	-3.6	-25.2	-22.0	-9.2	8.5	-12.5
			4.0	0.7	-1.7	-20.0	16.9	-6.9	5.8	6.7
		100	0.0	5.7	-5.0	8.7	7.4	-5.3	6.0	-3.9
			4.0	5.0	-3.8	-40.0	-49.9	-6.5	5.8	-4.2
	G	70	0.0	-	-	-	-	-	-	-
			2.5	6.0	-2.4	-26.6	17.2	-6.6	5.2	-8.2
			4.0	1.1	-2.6	21.2	-16.8	-8.5	5.6	6.9
		100	0.0	4.8	-5.3	-11.6	14.8	-5.0	7.0	2.5
			4.0	6.3	-4.9	26.2	-29.2	13.4	-9.6	-11.5
	NY	70	0.0	4.7	-4.2	-5.1	5.7	-4.7	4.1	1.5
			2.5	5.8	-4.5	-11.0	10.9	-4.4	6.4	-5.1
			4.0	-	-	-	-	-	-	-
		100	0.0	5.0	-5.2	-8.2	13.1	-5.0	5.7	2.4
			4.0	5.3	-5.6	-17.0	21.1	-10.4	9.3	6.7

- 100-mm AASHTO type C curb, impact speed of 85 km/hr and offset distance of 2.5 m
- 100-mm AASHTO type C curb, impact speed of 100 km/hr and offset distance of 4.0 m
- 100-mm AASHTO type G curb, impact speed of 70 km/hr and offset distance of 2.5 m
- 100-mm AASHTO type G curb, impact speed of 70 km/hr and offset distance of 4.0 m
- 100-mm AASHTO type G curb, impact speed of 100 km/hr and offset distance of 4.0 m

6.5 Summary

The finite element program LS-DYNA was used in the analysis of various curb-and-barrier systems subjected to impact by a 2000 kg pickup truck. The study involved the modified G4(1S) guardrail model that was validated in Chapter 4 installed inconjunction with two 150-mm curbs (i.e., AASHTO types B and D) and three 100-mm curbs (i.e., AASHTO types C and G and the 100-mm New York Curb).

The backfill terrain and the roadway terrain in the computer model simulations had a zero slope and the guardrail was positioned at either 0.0 m, 2.5 m or 4.0 m offset from the curbs. Three different impact conditions were considered:

1) 100 km/hr and 25 degrees (i.e., NCHRP Report 350 Test 3-11),

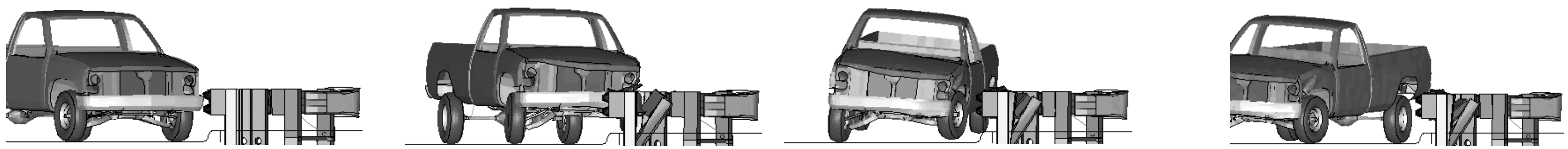
2) 85 km/hr and 25 degrees and

3) 70 km/hr and 25 degrees (i.e., NCHRP Report 350 Test 2-11) .

The data collected in the analyses included sequential snapshots of the impact event, acceleration-time histories, yaw-, pitch- and roll-time histories, w-beam tensile force-time histories and occupant risk information using the Test Risk Assessment Program. Table 6.8 provides a summary of the results of the curb-and-barrier impact study regarding success or failure of the system in each case based on the information obtained from the analyses and figures 6.21 - 6.49 provide a summary of general information regarding each curb-and-barrier impact simulation.

Table 6.8: Summary of curb-barrier impact study regarding success (✔) or failure (✘) of the system based on the results of the finite element analyses.

Impact Speed	**Curb Type**	**Offset Distance from Barrier to Curb**		
		0 m	**2.5 m**	**4 m**
70 km/hr	B	✔	✔ - high long. ORA - high lateral ORA	✔ - high lateral ORA
	C	✔	✔ ORA?	✔
	D	✔	✔ - high lateral ORA	✔
	G		✘ **-excess long. ORA** - high lateral ORA	✘ **-excess long. ORA** - high lateral ORA
	NY	✔	✔	
85 km/hr	B	✔	✘ **- override**	✘ **-excess long. ORA** - high lateral ORA
	C	✔	✘ **-excess long. ORA** **- override** - high lateral ORA	✔ - high long. ORA - high lateral ORA
100 km/hr	B	✔ - high pitch angle - high rail forces		✘ **- override** **-excess long. ORA** - high lateral ORA - high roll angle
	C	✘ **- override** **- rollover** **-excess long. ORA** - high trans. ORA		✘ **-excess long. ORA** **- override** - high lateral ORA - high roll angle
	D	✔ - high pitch angle - high rail forces		
	G	✔ - high pitch angle - high rail forces	✘ **- rollover** **- override** **-excess long. ORA** - high lateral ORA	✘ **- override** **-excess long. ORA** - high lateral ORA - high roll angle
	NY	✔ - high rail forces		✔ - high trajectory - high roll angle - high long. ORA - high lateral ORA

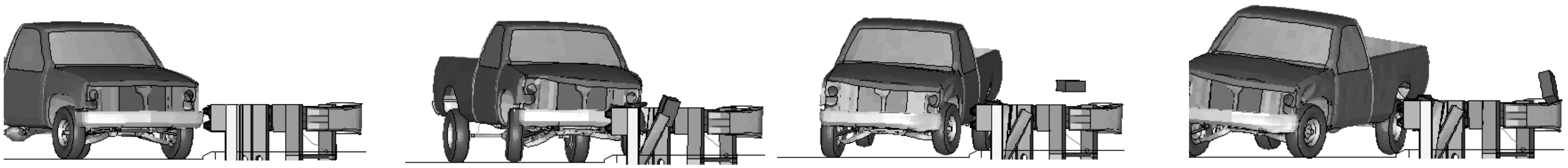


0.0 seconds 0.2 seconds 0.4 seconds 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	150-mm AASHTO Type B
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	70 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	21 degrees
• Maximum Roll Angle	-1.9 degrees
• Maximum Pitch Angle	-6.4 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	4.1 < 12 m/s
Lateral	-3.6
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-6.0 < 20 G's
Lateral	4.7
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-4.6
Lateral	3.3
Vertical	2.0
• THIV (km/hr)	16.3
• PHD (g's)	7.2
• ASI	0.47
• Maximum Force in W-Beam Rail	
Impact Region	127 kN
Upstream Anchor	-
Downstream Location	71.2 kN

Figure 6.21: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type B curb at **70 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

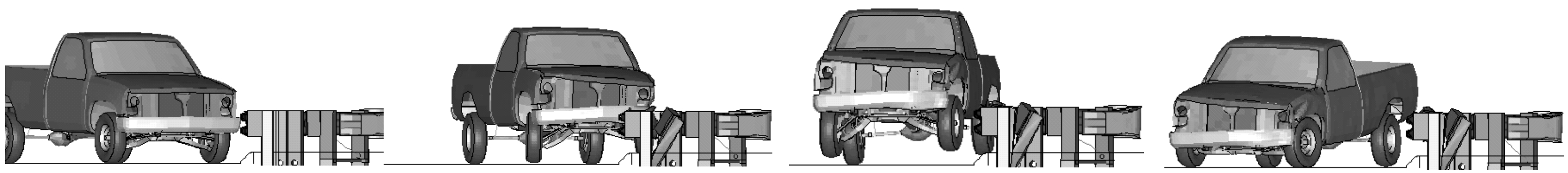


0.0 seconds 0.2 seconds 0.4 seconds 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type C
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	70 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	21 degrees
• Maximum Roll Angle	-7.0 degrees
• Maximum Pitch Angle	-3.7 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	4.2 < 12 m/s
Lateral	-4.2
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-6.3 < 20 G's
Lateral	7.5
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-4.0
Lateral	3.8
Vertical	1.7
• THIV (km/hr)	20.1
• PHD (g's)	9.7
• ASI	0.52
• Maximum Force in W-Beam Rail	
Impact Region	127 kN
Upstream Anchor	124 kN
Downstream Location	87.8 kN

Figure 6.22: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type C curb at **70 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

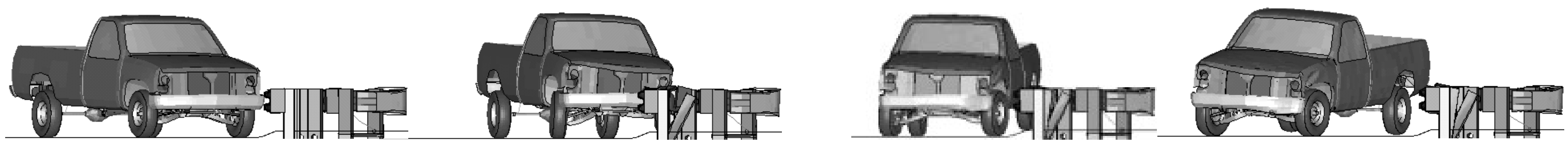


0.0 seconds | 0.2 seconds | 0.4 seconds | 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	150-mm AASHTO Type D
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	70 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	20.2 degrees
• Maximum Roll Angle	2.2 degrees
• Maximum Pitch Angle	3.5 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	4.3 < 12 m/s
Lateral	-4.1
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-6.6 < 20 G's
Lateral	6.7
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-4.6
Lateral	3.7
Vertical	-2.0
• THIV (km/hr)	20.7
• PHD (g's)	8.1
• ASI	0.50
• Maximum Force in W-Beam Rail	
Impact Region	128 kN
Upstream Anchor	127 kN
Downstream Location	82.9 kN

Figure 6.23: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type D curb at **70 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

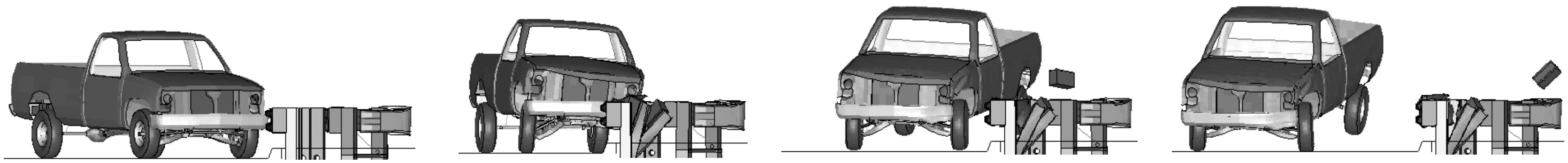


0.0 seconds | 0.2 seconds | 0.4 seconds | 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm New York Curb
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	70 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	21.3 degrees
• Maximum Roll Angle	-4.3 degrees
• Maximum Pitch Angle	-2.1 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	4.7 < 12 m/s
Lateral	-4.2
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-5.1 < 20 G's
Lateral	5.7
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-4.7
Lateral	4.1
Vertical	-1.5
• THIV (km/hr)	21.7
• PHD (g's)	7.2
• ASI	0.57
• Maximum Force in W-Beam Rail	
Impact Region	135 kN
Upstream Anchor	131 kN
Downstream Location	76.0 kN

Figure 6.24: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm New York curb at **70 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

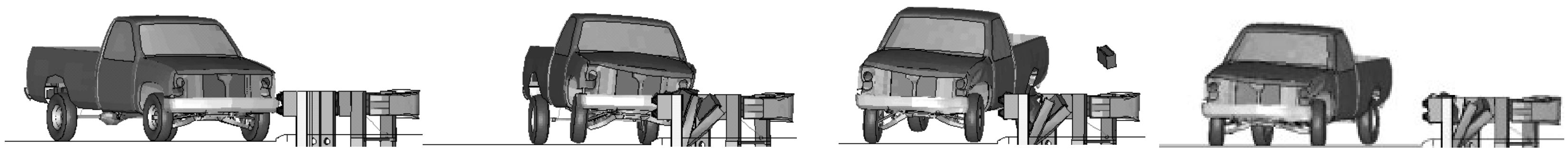


0.0 seconds — 0.2 seconds — 0.4 seconds — 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	150-mm AASHTO Type B
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	85 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	19.3 degrees
• Maximum Roll Angle	5.4 degrees
• Maximum Pitch Angle	-7.6 degrees
• Vehicle Trajectory	Moderate
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	4.2 < 12 m/s
Lateral	-4.1
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-8.1 < 20 G's
Lateral	10.6
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-4.2
Lateral	5.7
Vertical	4.2
• THIV (km/hr)	19.7
• PHD (g's)	15.9
• ASI	0.67
• Maximum Force in W-Beam Rail	
Impact Region	165 kN
Upstream Anchor	141 kN
Downstream Location	117 kN

Figure 6.25: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type B curb at **85 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

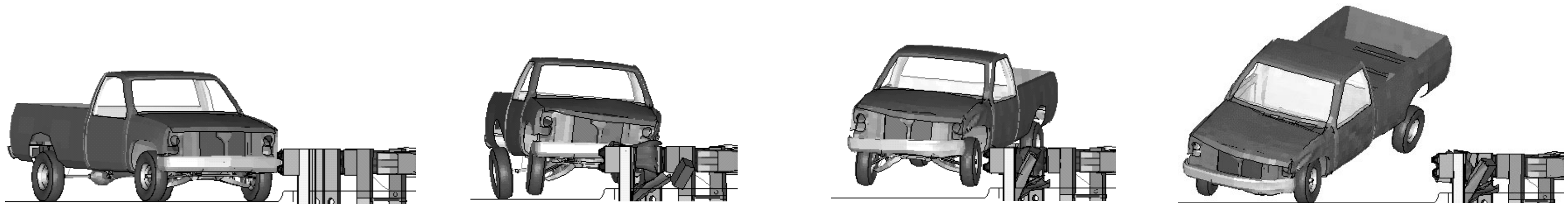


0.0 seconds | 0.2 seconds | 0.4 seconds | 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type C
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	85 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	18.5 degrees
• Maximum Roll Angle	8.2 degrees
• Maximum Pitch Angle	-3.3 degrees
• Vehicle Trajectory	Moderate
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	4.1 < 12 m/s
Lateral	-4.3
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-12.9 < 20 G's
Lateral	12.6
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-4.1
Lateral	5.5
Vertical	2.3
• THIV (km/hr)	19.7
• PHD (g's)	32.8
• ASI	0.67
• Maximum Force in W-Beam Rail	
Impact Region	170 kN
Upstream Anchor	142 kN
Downstream Location	122 kN

Figure 6.26: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type C curb at **85 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

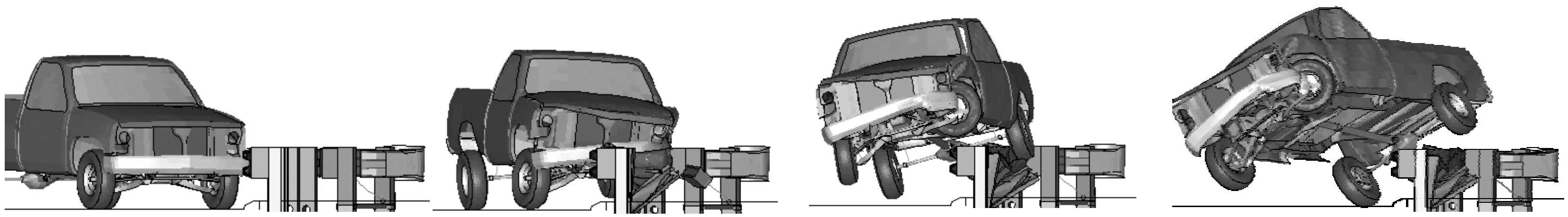


0.0 seconds 0.2 seconds 0.4 seconds 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	150-mm AASHTO Type B
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	22.4 degrees
• Maximum Roll Angle	-18.0 degrees
• Maximum Pitch Angle	-14.2 degrees
• Vehicle Trajectory	Significant
• Vehicle Stability	Questionable

• Occupant Impact Velocity (m/s)	
Longitudinal	5.5 < 12 m/s
Lateral	-5.0
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-11.0 < 20 G's
Lateral	14.9
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-5.4
Lateral	7.6
Vertical	3.3
• THIV (km/hr)	23.9
• PHD (g's)	33.4
• ASI	0.89
• Maximum Force in W-Beam Rail	
Impact Region	232 kN
Upstream Anchor	
Downstream Location	182 kN

Figure 6.27: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type B curb at **100 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

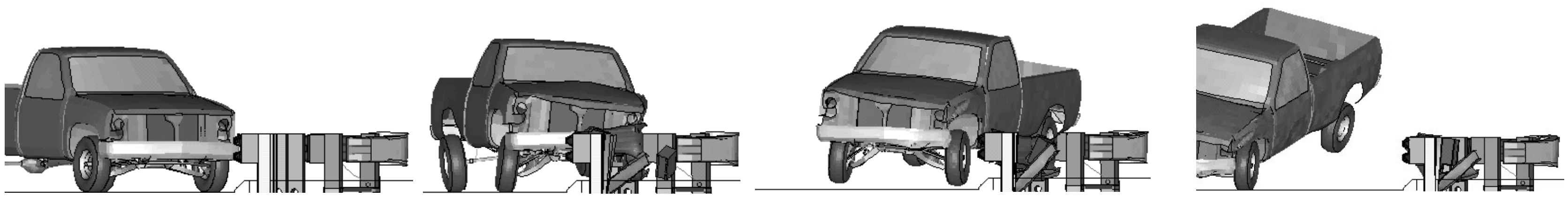


0.0 seconds | 0.2 seconds | 0.4 seconds | 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type C
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	29.5 degrees
• Maximum Roll Angle	31.3 degrees
• Maximum Pitch Angle	6.0 degrees
• Vehicle Trajectory	Excessive
• Vehicle Stability	Unsatisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	5.7 < 12 m/s
Lateral	-5.0
• Occupant Ridedown Deceleration (g's)	
Longitudinal	8.7 < 20 G's
Lateral	7.4
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-5.3
Lateral	6.0
Vertical	-3.9
• THIV (km/hr)	26.1
• PHD (g's)	17.5
• ASI	0.76
• Maximum Force in W-Beam Rail	
Impact Region	226 kN
Upstream Anchor	202 kN
Downstream Location	175 kN

Figure 6.28: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type C curb at **100 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

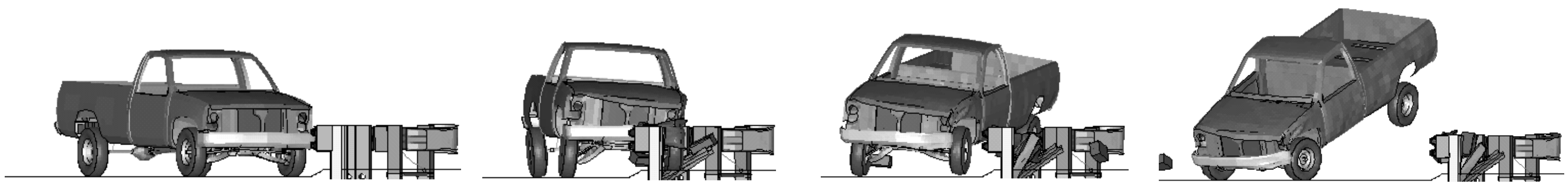


0.0 seconds | 0.2 seconds | 0.4 seconds | 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	150-mm AASHTO Type D
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	24.2 degrees
• Maximum Roll Angle	-12.5 degrees
• Maximum Pitch Angle	-14.3 degrees
• Vehicle Trajectory	Moderate
• Vehicle Stability	Questionable

• Occupant Impact Velocity (m/s)	
Longitudinal	5.9 < 12 m/s
Lateral	-4.8
• Occupant Ridedown Deceleration (g's)	
Longitudinal	14.0 < 20 G's
Lateral	15.9
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-5.4
Lateral	7.1
Vertical	-3.5
• THIV (km/hr)	24.9
• PHD (g's)	29.1
• ASI	0.85
• Maximum Force in W-Beam Rail	
Impact Region	243 kN
Upstream Anchor	210 kN
Downstream Location	183 kN

Figure 6.29: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type D curb at **100 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

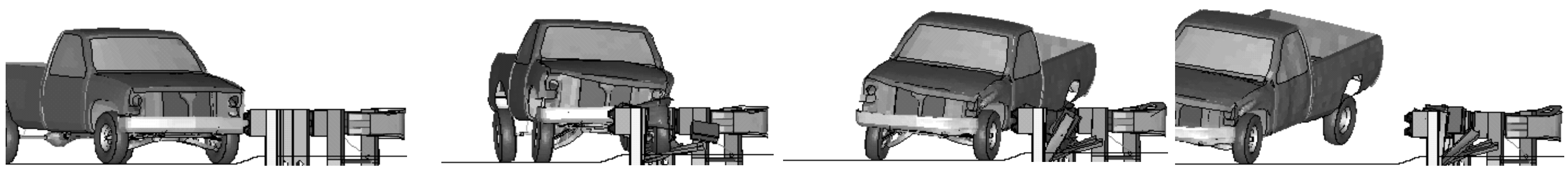


0.0 seconds | 0.2 seconds | 0.4 seconds | 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type G
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	23.0 degrees
• Maximum Roll Angle	-11.4 degrees
• Maximum Pitch Angle	-21.6 degrees
• Vehicle Trajectory	Moderate
• Vehicle Stability	Unsatisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	4.8 < 12 m/s
Lateral	-5.3
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-11.6 < 20 G's
Lateral	14.8
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-5.0
Lateral	7.0
Vertical	2.5
• THIV (km/hr)	23.8
• PHD (g's)	21.0
• ASI	0.83
• Maximum Force in W-Beam Rail	
Impact Region	223 kN
Upstream Anchor	
Downstream Location	174 kN

Figure 6.30: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type G curb at **100 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.

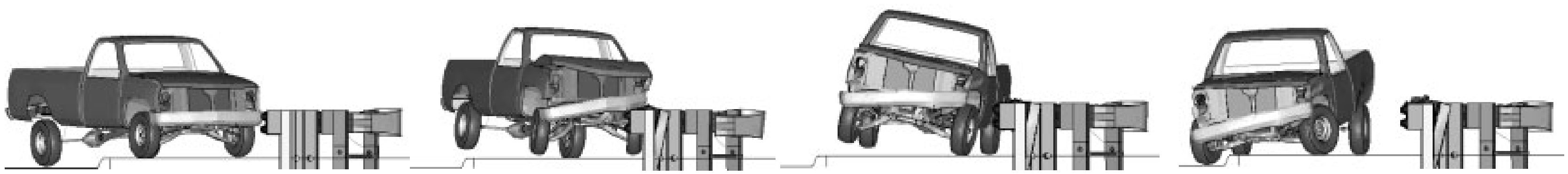


0.0 seconds 0.2 seconds 0.4 seconds 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm New York Curb
• Curb-Barrier Offset	0.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	23.5 degrees
• Maximum Roll Angle	-10.9 degrees
• Maximum Pitch Angle	-9.1 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	5.0 < 12 m/s
Lateral	-5.2
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-8.2 < 20 G's
Lateral	13.1
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-5.0
Lateral	5.7
Vertical	2.4
• THIV (km/hr)	23.5
• PHD (g's)	16.3
• ASI	0.72
• Maximum Force in W-Beam Rail	
Impact Region	231 kN
Upstream Anchor	198 kN
Downstream Location	178 kN

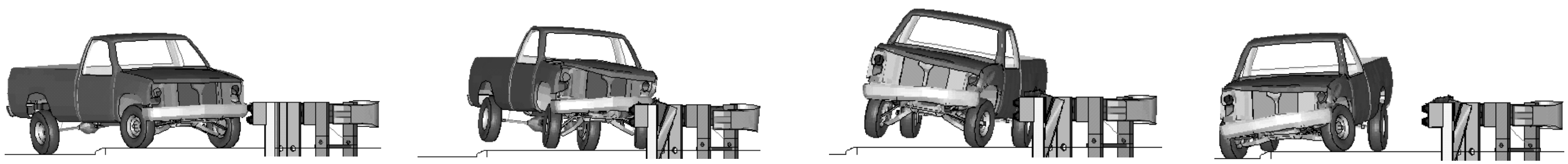
Figure 6.31: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm New York curb at **100 km/hr** and 25 degrees with barrier positioned at **0-m offset** from curb.



- Guardrail Type .... Modified G4(1S) with routed wood blockouts
- Curb Type .... 150-mm AASHTO Type B
- Curb-Barrier Offset .... 2.5 m
- Vehicle Model
  - Type .... Modified NCAC C2500
  - Mass .... 2000 kg
- Initial Conditions
  - Speed .... 100 km/hr
  - Angle .... 25 degrees
- Exit Conditions
  - Speed ....
  - Angle .... 13.7 degrees
- Maximum Roll Angle .... -11.9 degrees
- Maximum Pitch Angle .... -3.2 degrees
- Vehicle Trajectory .... Minimal
- Vehicle Stability .... Satisfactory

- Occupant Impact Velocity (m/s)
  - Longitudinal .... 3.5 < 12 m/s
  - Lateral .... -2.5
- Occupant Ridedown Deceleration (g's)
  - Longitudinal .... -15.1 < 20 G's
  - Lateral 19.4
- Maximum 50 ms Moving Average Acceleration (g's)
  - Longitudinal .... -4.6
  - Lateral .... -10.0
  - Vertical 7.4
- THIV (km/hr) 14.6
- PHD (g's) 51.9
- ASI 1.13
- Maximum Force in W-Beam Rail
  - Impact Region .... 95.0 kN
  - Upstream Anchor .... 88.7 kN
  - Downstream Location .... 68.6 kN

Figure 6.32: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type B curb at **70 km/hr** and 25 degrees with barrier positioned at **2.5-m offset** from curb.

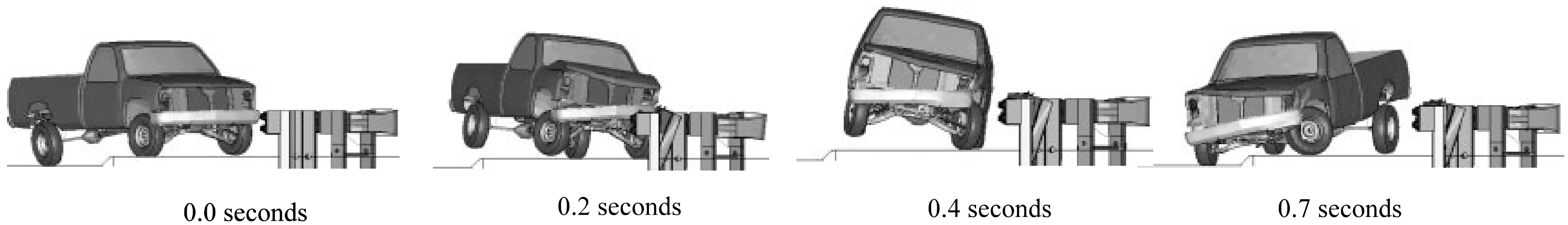


0.0 seconds | 0.2 seconds | 0.4 seconds | 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type C
• Curb-Barrier Offset	2.5 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	
• Maximum Roll Angle	
• Maximum Pitch Angle	
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	
Lateral	
• Occupant Ridedown Deceleration (g's)	
Longitudinal	
Lateral	
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	
Lateral	
Vertical	
• THIV (km/hr)	
• PHD (g's)	
• ASI	
• Maximum Force in W-Beam Rail	
Impact Region	
Upstream Anchor	
Downstream Location	

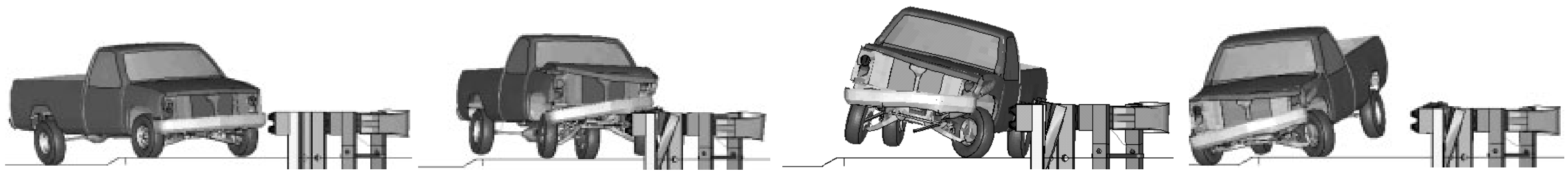
Figure 6.33: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type C curb at **70 km/hr** and 25 degrees with barrier positioned at **2.5-m offset** from curb.



• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	150-mm AASHTO Type D
• Curb-Barrier Offset	2.5 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	18.9 degrees
• Maximum Roll Angle	-11.4 degrees
• Maximum Pitch Angle	-5.2 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	-0.1 < 12 m/s
Lateral	-1.6
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-12.7 < 20 G's
Lateral	17.3
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-5.6
Lateral	5.8
Vertical	-7.7
• THIV (km/hr)	6.1
• PHD (g's)	34.2
• ASI	0.83
• Maximum Force in W-Beam Rail	
Impact Region	128 kN
Upstream Anchor	120 kN
Downstream Location	82.1 kN

Figure 6.34: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type D curb at **70 km/hr** and 25 degrees with barrier positioned at **2.5-m offset** from curb.

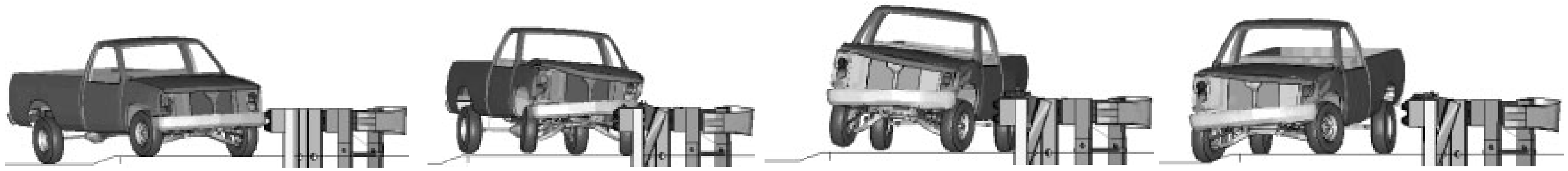


0.0 seconds   0.2 seconds   0.4 seconds   0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type G
• Curb-Barrier Offset	2.5 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	19.9 degrees
• Maximum Roll Angle	-14.1 degrees
• Maximum Pitch Angle	-6.3 degrees
• Vehicle Trajectory	Moderate
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	6.0 < 12 m/s
Lateral	-2.4
• Occupant Ridedown Deceleration (g’s)	
Longitudinal	-26.6 < 20 G’s ?
Lateral	17.2 ?
• Maximum 50 ms Moving Average Acceleration (g’s)	
Longitudinal	-6.6
Lateral	5.2
Vertical	-8.2
• THIV (km/hr)	21.9
• PHD (g’s)	79.6
• ASI	0.89
• Maximum Force in W-Beam Rail	
Impact Region	123 kN
Upstream Anchor	118 kN
Downstream Location	77.8 kN

Figure 6.35: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type G curb at **70 km/hr** and 25 degrees with barrier positioned at **2.5-m offset** from curb.

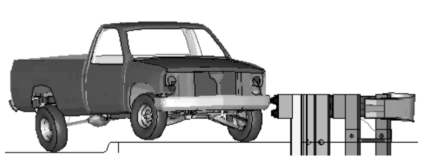


0.0 seconds 0.2 seconds 0.4 seconds 0.6 seconds

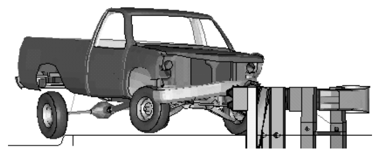
- Guardrail Type . . . . Modified G4(1S) with routed wood blockouts
- Curb Type . . . . 100-mm New York Curb
- Curb-Barrier Offset . . . . 2.5 m
- Vehicle Model
  - Type . . . . Modified NCAC C2500
  - Mass . . . . 2000 kg
- Initial Conditions
  - Speed . . . . 100 km/hr
  - Angle . . . . 25 degrees
- Exit Conditions
  - Speed . . . .
  - Angle . . . . 15.8 degrees
- Maximum Roll Angle . . . . -8.4 degrees
- Maximum Pitch Angle . . . . -5.2 degrees
- Vehicle Trajectory . . . . Minimal
- Vehicle Stability . . . . Satisfactory

- Occupant Impact Velocity (m/s)
  - Longitudinal . . . . 5.8 < 12 m/s
  - Lateral . . . . -4.5
- Occupant Ridedown Deceleration (g's)
  - Longitudinal . . . . -11.0 < 20 G's
  - Lateral 10.9
- Maximum 50 ms Moving Average Acceleration (g's)
  - Longitudinal . . . . -4.4
  - Lateral 6.4
  - Vertical . . . . -5.1
- THIV (km/hr) 23.2
- PHD (g's) 26.6
- ASI 0.88
- Maximum Force in W-Beam Rail
  - Impact Region . . . . 132 kN
  - Upstream Anchor . . . . 119 kN
  - Downstream Location . . . . 77.7 kN

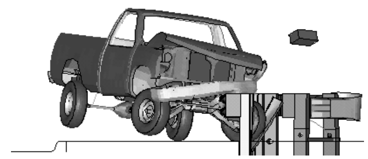
Figure 6.36: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm New York Curb curb at **70 km/hr** and 25 degrees with barrier positioned at **2.5-m offset** from curb.



0.0 seconds



0.1 seconds



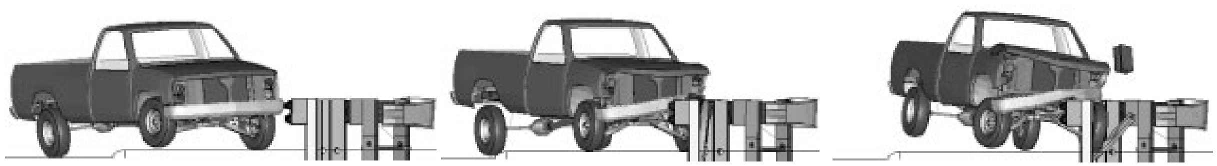
0.2 seconds

Analysis Terminated Prematurely

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type B
• Curb-Barrier Offset	2.5 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	85 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	
• Maximum Roll Angle	
• Maximum Pitch Angle	
• Vehicle Trajectory	Excessive
• Vehicle Stability	Questionable

• Occupant Impact Velocity (m/s)	
Longitudinal	
Lateral	
• Occupant Ridedown Deceleration (g's)	
Longitudinal	
Lateral	
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	
Lateral	
Vertical	
• THIV (km/hr)	
• PHD (g's)	
• ASI	
• Maximum Force in W-Beam Rail	
Impact Region	185 kN
Upstream Anchor	
Downstream Location	91.0 kN

Figure 6.37: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type B curb at **85 km/hr** and 25 degrees with barrier positioned at **2.5-m offset** from curb.



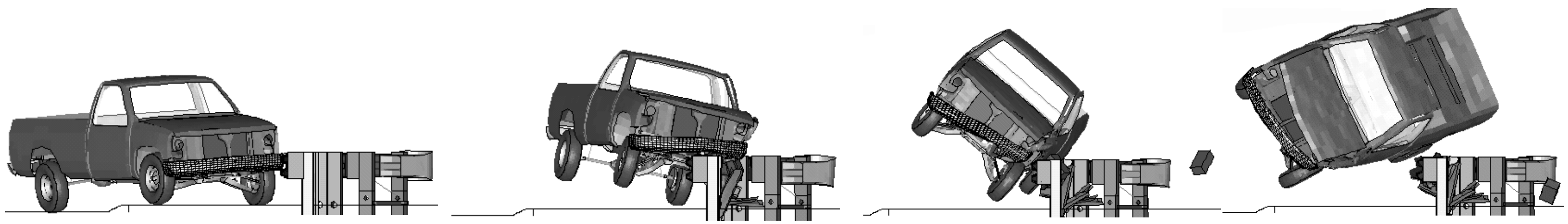
0.0 seconds   0.1 seconds   0.2 seconds

Analysis Terminated Prematurely

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type C
• Curb-Barrier Offset	2.5 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	85 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	NA
• Maximum Roll Angle	-6.1 degrees
• Maximum Pitch Angle	-2.2 degrees
• Vehicle Trajectory	Excessive
• Vehicle Stability	Questionable

• Occupant Impact Velocity (m/s)	
Longitudinal	6.1 < 12 m/s
Lateral	-3.6
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-25.2 < 20 G's
Lateral	22.0
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-9.2
Lateral	8.5
Vertical	-12.5
• THIV (km/hr)	25.2
• PHD (g's)	72.8
• ASI	1.68
• Maximum Force in W-Beam Rail	
Impact Region	205 kN
Upstream Anchor	177 kN
Downstream Location	102 kN

Figure 6.38: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type C curb at **85 km/hr** and 25 degrees with barrier positioned at **2.5-m offset** from curb.



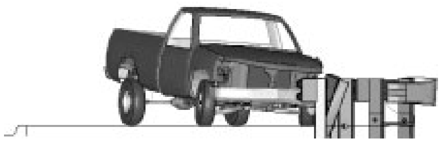
0.0 seconds | 0.2 seconds | 0.4 seconds | 0.6 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type G
• Curb-Barrier Offset	2.5 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	
• Maximum Roll Angle	
• Maximum Pitch Angle	
• Vehicle Trajectory	Excessive
• Vehicle Stability	Unsatisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	
Lateral	
• Occupant Ridedown Deceleration (g's)	
Longitudinal	
Lateral	
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	
Lateral	
Vertical	
• THIV (km/hr)	
• PHD (g's)	
• ASI	
• Maximum Force in W-Beam Rail	
Impact Region	
Upstream Anchor	
Downstream Location	

Figure 6.39: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type G curb at **100 km/hr** and 25 degrees with barrier positioned at **2.5-m offset** from curb.

0.0 seconds



0.2 seconds

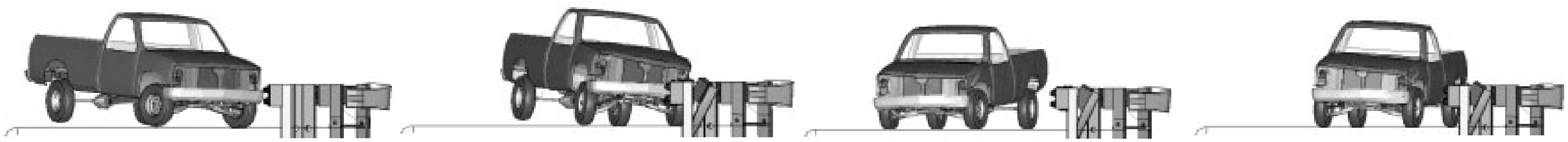
0.35 seconds

Analysis Terminated Prematurely

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	150-mm AASHTO Type B
• Curb-Barrier Offset	4.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	70 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	NA
• Maximum Roll Angle	-5.1 degrees
• Maximum Pitch Angle	-2.8 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	2.0 < 12 m/s
Lateral	-4.5
• Occupant Ridedown Deceleration (g's)	
Longitudinal	13.6< 20 G's
Lateral	-19.2
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-6.3
Lateral	8.3
Vertical	-6.7
• THIV (km/hr)	18.0
• PHD (g's)	41.4
• ASI	1.10
• Maximum Force in W-Beam Rail	
Impact Region	101 kN
Upstream Anchor	89.4 kN
Downstream Location	66.1 kN

Figure 6.40: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type B curb at **70 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.

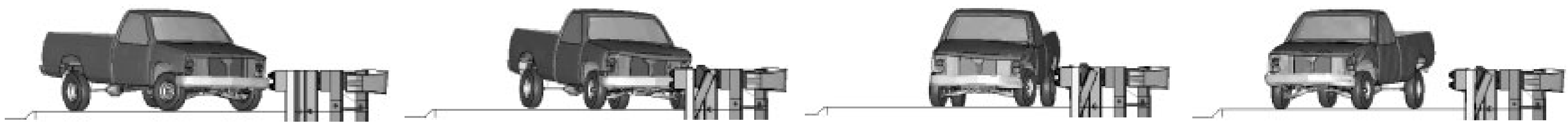


0.0 seconds — 0.2 seconds — 0.4 seconds — 0.64 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type C
• Curb-Barrier Offset	4.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	70 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	17.7
• Maximum Roll Angle	-7.6 degrees
• Maximum Pitch Angle	-2.7 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	1.6 < 12 m/s
Lateral	1.4
• Occupant Ridedown Deceleration (g's)	
Longitudinal	14.4< 20 G's
Lateral	13.8
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	6.9
Lateral	6.3
Vertical	6.8
• THIV (km/hr)	8.0
• PHD (g's)	38.9
• ASI	0.77
• Maximum Force in W-Beam Rail	
Impact Region	114 kN
Upstream Anchor	113 kN
Downstream Location	76.5 kN

Figure 6.41: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type C curb at **70 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.

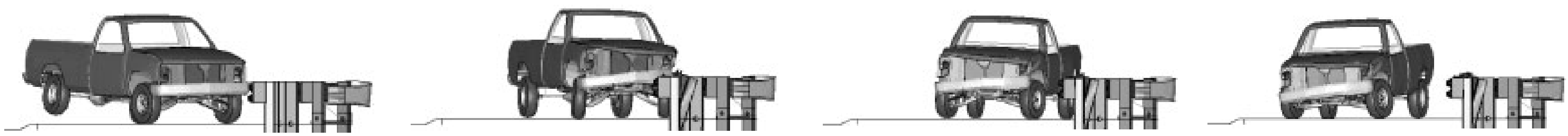


0.0 seconds 0.2 seconds 0.4 seconds 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	150-mm AASHTO Type D
• Curb-Barrier Offset	4.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	70 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	19.2
• Maximum Roll Angle	5.6 degrees
• Maximum Pitch Angle	-2.9 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	0.3 < 12 m/s
Lateral	-1.6
• Occupant Ridedown Deceleration (g's)	
Longitudinal	13.3< 20 G's
Lateral	14.4
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-3.9
Lateral	7.2
Vertical	5.1
• THIV (km/hr)	6.1
• PHD (g's)	49.7
• ASI	0.84
• Maximum Force in W-Beam Rail	
Impact Region	97.5 kN
Upstream Anchor	
Downstream Location	65.1 kN

Figure 6.42: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type D curb at **70 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.

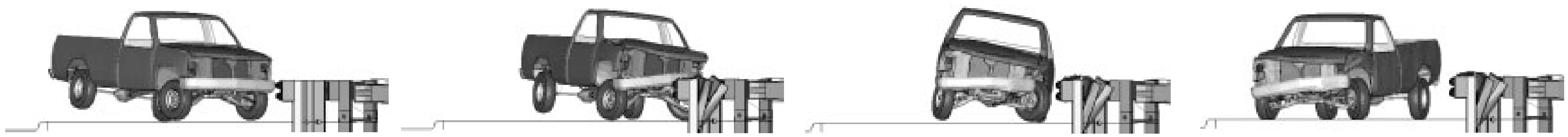


0.0 seconds 0.2 seconds 0.4 seconds 0.7 seconds

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type G
• Curb-Barrier Offset	4.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	70 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	14.6 degrees
• Maximum Roll Angle	4.4 degrees
• Maximum Pitch Angle	-3.4 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	1.1 < 12 m/s
Lateral	-2.6
• Occupant Ridedown Deceleration (g's)	
Longitudinal	21.2> 20 G's
Lateral	16.8
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-8.5
Lateral	5.6
Vertical	6.9
• THIV (km/hr)	10.5
• PHD (g's)	39.2
• ASI	0.80
• Maximum Force in W-Beam Rail	
Impact Region	130 kN
Upstream Anchor	116 kN
Downstream Location	78.8 kN

Figure 6.43: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type G curb at **70 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.

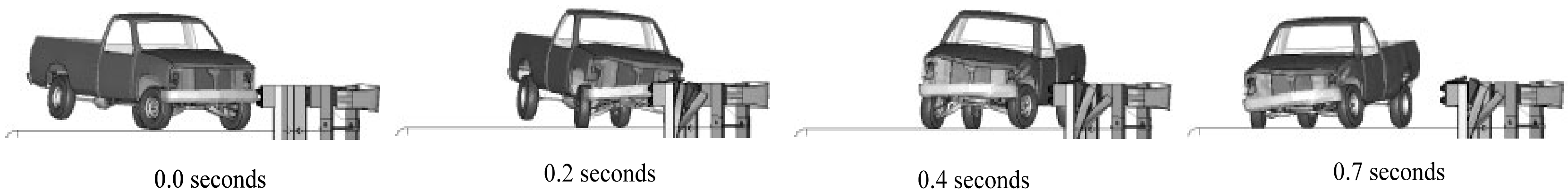


0.0 seconds   0.2 seconds   0.4 seconds   0.7 seconds

- Guardrail Type . . . . Modified G4(1S) with routed wood blockouts
- Curb Type . . . . 150-mm AASHTO Type B
- Curb-Barrier Offset . . . . 4.0 m
- Vehicle Model
  - Type . . . . Modified NCAC C2500
  - Mass . . . . 2000 kg
- Initial Conditions
  - Speed . . . . 85 km/hr
  - Angle . . . . 25 degrees
- Exit Conditions
  - Speed . . . .
  - Angle . . . . 18.9 degrees
- Maximum Roll Angle . . . . -10.8 degrees
- Maximum Pitch Angle . . . . -2.0 degrees
- Vehicle Trajectory . . . . Minimal
- Vehicle Stability . . . . Satisfactory

- Occupant Impact Velocity (m/s)
  - Longitudinal . . . . $0.1 < 12$ m/s
  - Lateral . . . . -2.6
- Occupant Ridedown Deceleration (g’s)
  - Longitudinal . . . . $-31.1 > 20$ G’s
  - Lateral 29.0
- Maximum 50 ms Moving Average Acceleration (g’s)
  - Longitudinal . . . . -14.7
  - Lateral 10.1
  - Vertical . . . . -9.0
- THIV (km/hr) 9.7
- PHD (g’s) 68.6
- ASI 1.66
- Maximum Force in W-Beam Rail
  - Impact Region . . . . 171 kN
  - Upstream Anchor . . . . 143 kN
  - Downstream Location . . . . 103 kN

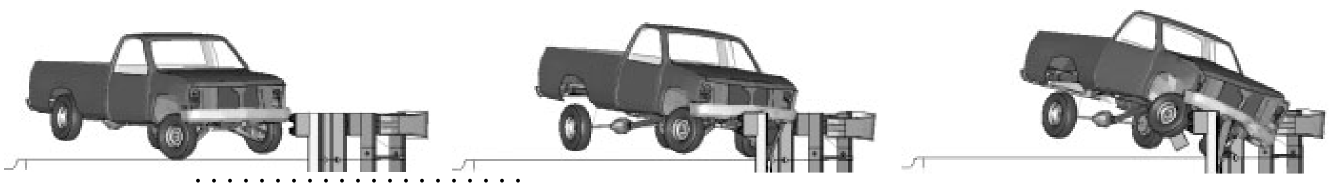
Figure 6.44: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type B curb at **85 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.



• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type C
• Curb-Barrier Offset	4.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	85 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	17.0 degrees
• Maximum Roll Angle	-6.3 degrees
• Maximum Pitch Angle	-3.2 degrees
• Vehicle Trajectory	Minimal
• Vehicle Stability	Satisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	0.7 < 12 m/s
Lateral	-1.7
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-20.0 = 20 G's
Lateral	16.9
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	-6.9
Lateral	5.8
Vertical	6.7
• THIV (km/hr)	5.6
• PHD (g's)	50.7
• ASI	0.81
• Maximum Force in W-Beam Rail	
Impact Region	171 kN
Upstream Anchor	148 kN
Downstream Location	120 kN

Figure 6.45: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type C curb at **85 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.



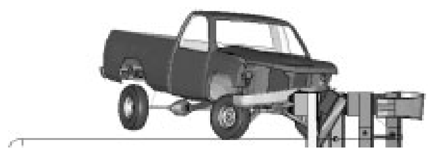
0.0 seconds 0.1 seconds 0.2 seconds

Analysis Stopped After Override

- Guardrail Type . . . . Modified G4(1S) with routed wood blockouts
- Curb Type . . . . 150-mm AASHTO Type B
- Curb-Barrier Offset . . . . 4.0 m
- Vehicle Model
  - Type . . . . Modified NCAC C2500
  - Mass . . . . 2000 kg
- Initial Conditions
  - Speed . . . . 100 km/hr
  - Angle . . . . 25 degrees
- Exit Conditions
  - Speed . . . .
  - Angle . . . . NA
- Maximum Roll Angle . . . . -19.6 degrees
- Maximum Pitch Angle . . . . -6.2 degrees
- Vehicle Trajectory . . . . Excessive
- Vehicle Stability . . . . Unsatisfactory
- Occupant Impact Velocity (m/s)
  - Longitudinal . . . . 3.6 < 12 m/s
  - Lateral 0.3
- Occupant Ridedown Deceleration (g's)
  - Longitudinal . . . . -40.0 > 20 G's
  - Lateral . . . . -49.9
- Maximum 50 ms Moving Average Acceleration (g's)
  - Longitudinal . . . . -13.1
  - Lateral 9.6
  - Vertical . . . . -14.6
- THIV (km/hr) 13.1
- PHD (g's) 143.3
- ASI 1.79
- Maximum Force in W-Beam Rail
  - Impact Region . . . .
  - Upstream Anchor . . . .
  - Downstream Location . . . .

Figure 6.46: Summary of Analysis Results for C2500 impact with modified G4(1S) and 150-mm AASHTO Type B curb at **100 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.

0.0 seconds



0.1 seconds

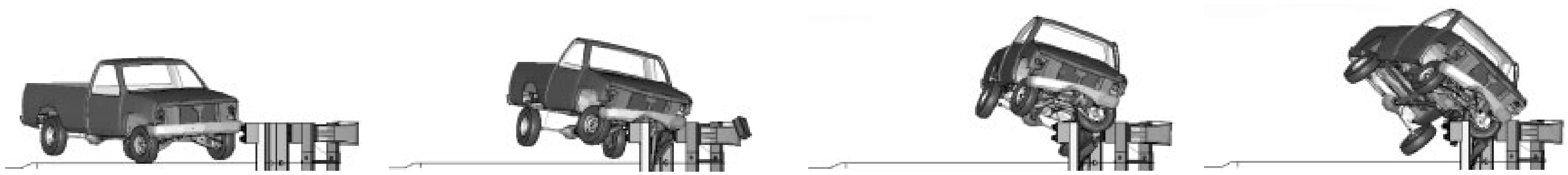
0.13 seconds

Analysis Terminated Prematurely

- Guardrail Type . . . . Modified G4(1S) with routed wood blockouts
- Curb Type . . . . 100-mm AASHTO Type C
- Curb-Barrier Offset . . . . 4.0 m
- Vehicle Model
  - Type . . . . Modified NCAC C2500
  - Mass . . . . 2000 kg
- Initial Conditions
  - Speed . . . . 100 km/hr
  - Angle . . . . 25 degrees
- Exit Conditions
  - Speed . . . .
  - Angle . . . . NA
- Maximum Roll Angle . . . . -6.7 degrees
- Maximum Pitch Angle . . . . -3.5 degrees
- Vehicle Trajectory . . . . Excessive
- Vehicle Stability . . . . Unsatisfactory

- Occupant Impact Velocity (m/s)
  - Longitudinal . . . . 5.0 < 12 m/s
  - Lateral . . . . -3.8
- Occupant Ridedown Deceleration (g's)
  - Longitudinal . . . . -40.0 > 20 G's
  - Lateral . . . . -49.9
- Maximum 50 ms Moving Average Acceleration (g's)
  - Longitudinal . . . . -6.5
  - Lateral 5.8
  - Vertical . . . . -4.2
- THIV (km/hr) 23.7
- PHD (g's) 33.5
- ASI 0.87
- Maximum Force in W-Beam Rail
  - Impact Region . . . .
  - Upstream Anchor . . . .
  - Downstream Location . . . .

Figure 6.47: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type C curb at **100 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.



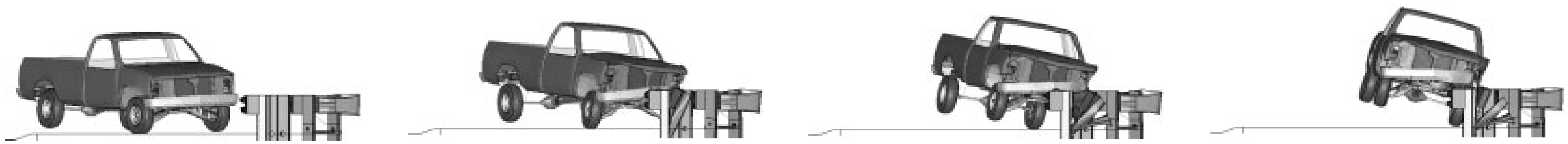
0.0 seconds 0.2 seconds 0.4 seconds 0.6 seconds

Analysis Stopped After Override

• Guardrail Type	Modified G4(1S) with routed wood blockouts
• Curb Type	100-mm AASHTO Type G
• Curb-Barrier Offset	4.0 m
• Vehicle Model	
Type	Modified NCAC C2500
Mass	2000 kg
• Initial Conditions	
Speed	100 km/hr
Angle	25 degrees
• Exit Conditions	
Speed	
Angle	NA
• Maximum Roll Angle	-45.1 degrees
• Maximum Pitch Angle	3.5 degrees
• Vehicle Trajectory	Excessive
• Vehicle Stability	Unsatisfactory

• Occupant Impact Velocity (m/s)	
Longitudinal	6.3 < 12 m/s
Lateral	-4.9
• Occupant Ridedown Deceleration (g's)	
Longitudinal	-26.2 > 20 G's
Lateral	-29.2
• Maximum 50 ms Moving Average Acceleration (g's)	
Longitudinal	13.4
Lateral	-9.6
Vertical	-11.5
• THIV (km/hr)	28.6
• PHD (g's)	83.4
• ASI	1.45
• Maximum Force in W-Beam Rail	
Impact Region	
Upstream Anchor	
Downstream Location	

Figure 6.48: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm AASHTO Type G curb at **100 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.



0.0 seconds 0.1 seconds 0.2 seconds 0.26 seconds

Analysis Terminated Prematurely

- Guardrail Type . . . . Modified G4(1S) with routed wood blockouts
- Curb Type . . . . 100-mm New York Curb
- Curb-Barrier Offset . . . . 4.0 m
- Vehicle Model
  - Type . . . . Modified NCAC C2500
  - Mass . . . . 2000 kg
- Initial Conditions
  - Speed . . . . 100 km/hr
  - Angle . . . . 25 degrees
- Exit Conditions
  - Speed . . . .
  - Angle . . . . NA
- Maximum Roll Angle . . . . -15.2 degrees
- Maximum Pitch Angle . . . . 3.1 degrees
- Vehicle Trajectory . . . . Excessive
- Vehicle Stability . . . . Unsatisfactory

- Occupant Impact Velocity (m/s)
  - Longitudinal . . . . $5.3 < 12$ m/s
  - Lateral . . . . -5.6
- Occupant Ridedown Deceleration (g's)
  - Longitudinal . . . . $-17.0 < 20$ G's
  - Lateral . . . . -21.1
- Maximum 50 ms Moving Average Acceleration (g's)
  - Longitudinal . . . . -10.4
  - Lateral 9.3
  - Vertical 6.7
- THIV (km/hr) 24.6
- PHD (g's) 43.0
- ASI 1.12
- Maximum Force in W-Beam Rail
  - Impact Region . . . .
  - Upstream Anchor . . . .
  - Downstream Location . . . .

Figure 6.49: Summary of Analysis Results for C2500 impact with modified G4(1S) and 100-mm New York curb at **100 km/hr** and 25 degrees with barrier positioned at **4.0-m offset** from curb.

VII. SYNTHESIS OF ANALYSIS RESULTS

7.1 Introduction

The analyses of vehicle impact with curbs and curb-barrier combinations conducted in this study were limited to one vehicle type, a 2000-kg pickup truck. Thus, guidelines based solely on the results of those analyses would only be applicable to that one type of vehicle. In order to develop a more general set of guidelines, additional data is needed that will provide more information about the response of a broader range of vehicle types. The literature provides an adequate amount of information on the response of various types of cars traversing curbs and also a limited amount of information from the results of full-scale crash tests regarding both cars and pickup trucks impacting curb-barrier combinations. The information from the current study will be synthesized and combined with the results of prior studies such that general guidelines can be developed for the use and installation of curbs and curb-barrier combinations along high-speed roadways.

There are many factors that influence vehicle behavior when traversing curbs, 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, all the data that have been collected from full-scale tests and computer simulations suggests that total loss of control is unlikely except in extreme cases. A more important issue, however, 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). 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 increase in bumper height during 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 roadside hardware devices.

Two of the studies identified in the literature addressed the issue of override and underride indirectly using both full-scale testing and computer simulation: Olsen *et al. (22)* and Holloway *et al.(25)*. In those studies the response of various types of cars traversing a number of different curb types was obtained and the information was used to assess vehicle stability and to estimate the potential for barrier override and underride. The types of data that were collected in their studies were roll and pitch displacement-time histories and also relative bumper trajectory-time history of the vehicles when traversing curbs. There were various impact conditions and curb types investigated in those studies, however, all impact conditions were considered equally likely since data are not available to discern the most probable impact conditions of roadside accidents. Only the maximum values of angular displacement and bumper heights during trajectory from the various studies will be considered when synthesizing the data. It should be noted that the maximum encroachment angle of both the Olsen *et al*. study and the Holloway *et al*. study was 20 degrees, whereas the maximum encroachment angle used in the current study was 25 degrees. Furthermore, the vehicle used in the Olsen *et al*. study was a 1965 Ford four-door sedan and it may be questionable whether or not those results are representative of the current vehicle fleet. The results and conclusions from Olsen's study, however, were similar to those obtained in both the Holloway *et al*. study and the current study.

7.2 Vehicle Curb Traversal Tests and Simulation Results

The vehicle encroachment angle and speed in the various studies ranged from 5 degrees to 25 degrees and 48 km/hr to 120 km/hr, respectively.

7.2.1 Maximum Roll and Pitch Angles

Based on the results of this research and on conclusions made in previous studies the following statements can be made. Maximum roll angles of vehicles crossing curbs decrease as encroachment angles increase, and they are only slightly affected by impact speed. The maximum roll angle also increases as curb height increases, but curb shape has very little influence on roll angle, especially at higher impact speeds. Maximum pitch angle increases as encroachment angle increases, but tends to be independent of vehicle speed. The maximum pitch angle increases slightly as curb height increases, but curb shape has no discernable influence on pitch angle.

Table 7.1 provides a summary of the maximum roll and pitch angles of vehicles crossing various types of curbs for particular vehicle types and for a range of impact conditions. For the cases involving both small and large cars crossing 150 mm high curbs, the maximum roll angle ranged from 11.0 to 12.4 degrees, whereas, the pickup truck crossing 150 mm high curbs resulted in a maximum roll angle of 7.6 degrees. The maximum pitch angles in all cases of vehicles crossing 150 mm high curbs were very low and ranged from 1.8 to 3.3 degrees.

For cases involving the small and large cars crossing 100 mm high curbs, the maximum roll angle ranged from 7.0 to 8.1 degrees, and the maximum roll angle of the pickup truck was 6.0 degrees. As with the 150-mm curb cases, the maximum pitch angles of vehicles crossing the 100 mm high curbs were insignificant and ranged from 0.7 to 2.7 degrees.

7.2.2 Front Bumper Trajectory

The trajectory of the front bumper is dependent on curb shape. As curb height increases and as the slope of the curb face increases, the maximum vertical position of the front bumper increases. Curb height, however, has much more influence than does the slope of the curb face. Regarding impact conditions, the maximum vertical component of trajectory of the bumper is nearly independent of encroachment speed, but it increases as impact angle increases.

Table 7.1 provides a summary of lateral offset distances for which bumper trajectory plots indicate a potential for vehicle underride and override of a standard strong-post w-beam guardrail system. Considering the results from all studies, underride is possible for cases involving cars impacting 150-mm curbs placed in conjunction with a w-beam guardrail when the barrier is offset at distances less than 1.1 m from the curb. The studies also suggests, however, that impact with a 100-mm curb placed in conjunction with a guardrail is not likely to result in underride.

At low encroachment angles (e.g., 5 degrees) onto the 150-mm curbs, the trajectory of the front bumper was such that its vertical position exceeded the height of a standard strong-post w-beam guardrail at offset distances as low as 0.5 m for all vehicle types. As the impact angle increased, so did the lateral distance behind the curb for which the bumper trajectory was sufficient to override a guardrail. For example, computer simulations of the pickup truck traversing curbs at 100 km/hr and 25 degrees indicated that the vertical component of trajectory of the front bumper exceeded the height of a standard guardrail for offset distances as great as 7.0 m. Based on bumper trajectory data of vehicles traversing curbs, override of a strong-post w-beam guardrail is probable for all curb-guardrail cases involving 150-mm curbs when the barrier is placed between 0.5 and 7.0 m behind the curb for the range of impact conditions investigated. The potential for override is less for 100-mm curbs, however, pickup trucks crossing the curbs may vault over a guardrail that is positioned at 0.6 - 7.0 m behind the curb.

The curb traversal studies indicate that the most appropriate placement of curbs with respect to guardrail is to place the curb underneath the guardrail behind the face of the w-beam.

Table 7.1: Summary of curb tracking results from various studies

Curb Height	Vehicle Type	Curb Types	Impact Conditions		Results		Curb-barrier offset dist.	
			Angles (deg)	Speeds (km/hr)	Max Roll (deg)	Max Pitch (deg)	Underride (m)	Override (m)
150 mm	817-kg car[1]	AASHTO I and Lip curb	5, 12.5, 20	72, 80 and 89	12.4	1.8	< 1.1	0.5 - 3.0
	1905-kg sedan[2]	AASHTO B and D	5, 10, 12.5, 20	48, 72, 97 and 121	13.0	3.0	< 0.6	0.9 - 3.6
	2043-kg LTD[3]	AASHTO I and Lip curb	5, 12.5, 20	72, 80 and 89	11.0	2.0	< 0.9	0.6 - 3.7
	2000-kg pickup	AASHTO A, B and D	5, 15, 25	70 and 100	7.6	3.3	Underride not likely	0.5 - 7.0
100 mm	817-kg car[1]	Lip curb	5, 12.5, 20	72, 80 and 89	8.1	1.6	Underride not likely	Override not likely
	1905-kg sedan[2]	AASHTO G	5, 10, 12.5, 20	48, 72, 97 and 121	7.0	1.0	Underride not likely	Override not likely
	2043-kg LTD[3]	Lip curb	5, 12.5, 20	72, 80 and 89	7.9	0.7	Underride not likely	Override not likely
	2000-kg pickup	AASHTO C, G and New	5, 15, 25	70 and 100	6.0	2.7	Underride not likely	0.6 - 7.0

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[1]Holloway *et al*. study *(25)*

[2]Olsen *et al*. study *(22)*

[3]Holloway *et al*. study *(25)*

7.2.3 Non-Tracking Impact

The analysis of non-tracking impacts was beyond the scope of research in this dissertation, however, there were a few studies identified in the literature review that addressed this issue using analytical methods, computer simulation and full-scale tests.*(25)(33)(34)*. Holloway *et al.* used the HVOSM computer program to simulate non-tracking impacts of both a small car (e.g., 817 kg) and a large car (e.g., 2043 kg) with a 100-mm lip curb, 150-mm lip curb and the AASHTO type I curb.*(25)* They found that these curbs may be traversable over a wide range of vehicle orientations and impact conditions and that they pose little threat of vehicle rollovers during impact, however, their models were not validated with test results for those types of impact conditions.

Copperrider *et al.* used full-scale tests to investigate the rollover propensity of a wide range of vehicle types tripped by either a 150-mm curb or by soil.*(33)* Their tests involved towing the vehicles sideways and releasing them just prior to impact with the curb or soil. They found that the duration of contact between the tires and the tripping mechanism (e.g., curb or soil) was the most influential factor affecting vehicle rollover. Although curb impacts resulted in much higher decelerations, the peak angular velocities were very similar in both the curb trip tests and the soil trip tests. Consequently, both are likely to result in vehicle rollover.

Based on the results found in these studies it is difficult to discern whether or not curbs are of any greater hazzard than a simple soil and sod roadside. A more direct method of testing or simulating non-tracking impacts of vehicles with curbs and of vehicles with soil-and-sod needs to be undertaken. Realistic vehicle maneuvers representing more probable impact orientations should also be used in such a test/simulation program.

7.3 Curb-Guardrail Tests and Simulation Results

The conclusions presented in the previous section regarding vehicle override and underride of guardrail barriers were estimated based on the trajectory of the front bumper of vehicles traversing curbs. Another factor that must be considered in such an event is the interaction of the vehicle with the barrier. The results of full-scale crash tests and finite element simulations demonstrate that vehicle impact with curb-guardrail systems will result in more severe impact conditions, and thus poorer performance of the guardrail, than would be the case if a curb were not present. Crash tests and computer analyses have been conducted in which the curb was placed underneath the rail behind the face of the w-beam to minimize the potential for a vehicle to strike the curb. The general outcome in those cases included excessive vertical trajectory of the vehicle and significant damage to the guardrail.

Table 2.5 in the literature review presented a summary of full-scale crash test results of curb-guardrail combinations where curbs were located behind the face of the w-beam of various strong-post guardrail systems. Table 2.5 is repeated here as table 7.2 for convenience. The impact speed in those tests ranged from 96.1 km/hr to 103.2 km/hr and impact angles ranged from 20 degrees to 28.6 degrees. The guardrail safely contained and

Table 7.2: Summary of full-scale crash tests of curb-guardrail combinations with curb located behind face of guardrail

Literature Reference	Testing Agency	Test No.	Vehicle Type	Speed and Angle	Curb Type	Guardrail Type	Result	Comment
Holloway *et al. (26)*	MwRSF	M06C-1	1985 Ford LTD (2041 kg)	96.1 km/hr 25.1 degrees	152 mm vertical curb	G4(1S)	Passed	smoothly redirected
Bryden and Phillips *(27)*	NYDOT		Dodge Station Wagon (2041 kg)	100 km/hr 26 degrees	152 mm vertical curb	Thrie-Beam Bridge Rail	Passed	smoothly redirected
FHWA Memorandum Feb 1992 *(28)*	ENSCO	1862-1-88	3/4-ton Pickup Truck (2449 kg)	100 km/hr 20 degrees	203 mm AASHTO A	G4(1S)	Failed	vehicle vaulted over rail
		1862-4-89	Small Car (820 kg)	100 km/hr 20 degrees	152 mm Asphalt Dike	G4(1S)	Passed	smoothly redirected
		1862-5-89	Large Car Sedan (2041 kg)	100 km/hr 25 degrees	152 mm Asphalt Dike	G4(1S)	Failed	vehicle vaulted over rail
		1862-12-90	Large Car Sedan (2449 kg)	100 km/hr 25 degrees	100 mm AASHTO G	G4(1S)	Passed	vehicle was airborn but did not vault
		1862-13-91	Large Car Sedan (2041 kg)	100 km/hr 25 degrees	152 mm Asphalt Dike	G4(1S) stiffened with w-beam	Passed	
		1862-14-91	Large Car Sedan (2041 kg)	100 km/hr 25 degrees	152 mm Asphalt Dike	G4(1S) stiffened with rub rail	Failed	vehicle speed change at redirection was too high
Polivka, *et al. (29)*	MwRSF	NEC-1	1991 GMC 3/4-ton Pickup (2,000 kg)	103.2 km/hr 24.5 degrees	102 mm AASHTO G	G4(1S)-mod with wood blockout	Failed	Excessive anchor movement / Guardrail ruptured
Polivka *et al. (30)*	MwRSF	NEC-2	1994 GMC 3/4-ton Pickup (2,000 kg)	100.3 km/hr 28.6 degrees	102 mm AASHTO G	G4(1S)-mod with wood blockout nested w-beam	Passed	vehicle experienced extreme trajectory but did not vault over rail
Bullard and Menges *(32)*	TTI	404201-1	1995 Chevrolet 3/4-ton Pickup (2000 kg)	101.8 km/hr 25.2 degrees	100 mm CDOT curb	G4(2W)	Passed	Significant guardrail damage and anchor movement

redirected the vehicle in cases where the wheels of the vehicle did not mount the curb during impact. Those tests were primarily limited to small cars as test vehicles, however, some cases involving large car sedans were also successful when vertical curbs were used or when the guardrail was stiffened. Four full-scale tests were conducted using 3/4-ton pickup trucks. In each of those tests the tires of the vehicle mounted the curb during impact and resulted in either excessive vertical trajectory of the vehicle or significant damage to the guardrail. Two of those tests did not satisfy safety requirements while two other tests were successful. The failure in one case was due to barrier override and in another case guardrail rupture was the cause of failure. The two successful tests were: 1) MwRSF Test NEC-2 which involved a 102-mm curb placed underneath a modified G4(1S) with wood blockouts and stiffened with nested w-beams and 2) TTI test 404201-1 which involved a 100-mm curb placed underneath the G4(2W) guardrail. The repeatability of those tests, however, are questionable due to the excessive vertical trajectory of the vehicle during impact in test NEC-2 and the excessive damage to the guardrail in test 404201-1 (refer to figures 2.8 and 2.11).

The analyses conducted in the current research involved the use of finite element simulation to investigate the response of a 3/4-ton pickup truck impacting curb-barrier systems in which the modified G4(1S) guardrail with wood blockouts was positioned at 0-m, 2.5-m and 4.0-m offset distances from curbs. The curbs used in the study had heights of 100 mm and 150 mm. The backfill area behind the curbs was modeled with rigid elements using a dynamic coefficient of friction of 0.82 between the tires of the vehicle and the ground surface. It should be noted that the interaction between the tires and ground in these analyses may not accurately represent cases where a backfill material is composed primarily of soft soil. The impact angle was 25 degrees in all simulations and impact speeds of 70 km/hr, 85 km/hr and 100 km/hr were investigated (refer to table 6.8 for summary of results).

The results of the pickup truck impacting the curb-barrier combination at 0-m offset distance (i.e., curbs under the face of the barrier) at speeds of 70 km/hr and 85 km/hr indicate that the vehicle would remain stable throughout the impact event and that barrier damage would be minimal regardless of the type of curb used. The bumper of the pickup was above the rail during redirection in one of the cases involving the 150-mm AASHTO type D curb, but the potential for override of the barrier was considered minimal (refer to the figures in Appendix VIII).

At the higher impact speed of 100 km/hr the analyses provided mixed conclusions. In one case involving the 100 mm high AASHTO type C curb the vehicle vaulted over the guardrail, whereas vaulting was not a serious issue in the other cases. The difference in this particular case was attributed to a wheel snag against a blockout early in the impact event which affected the way the vehicle interacted with the barrier throughout the remainder of the event. Wheel snag is common in impacts with strong-post w-beam guardrails and similar results are possible for cases involving any of the curb types. It was also concluded that vehicle stability may be an issue during redirection due to the high pitch angles of the vehicle when exiting the system. Furthermore, the tensile forces in the w-beam were high during impact indicating potential for rail rupture at the splice connections, especially for the cases involving the 150-mm curbs. The most promising combination involved the 100-mm New York curb. This combination resulted in safe redirection of the vehicle although the tensile forces in the rail were somewhat high.

The results of the finite element analyses regarding high speed impact indicated that the roll angle and pitch angle of the vehicle after traversing curbs had a significant influence on the kinematics of the vehicle during impact with the guardrail for cases involving offset distances of 2.5 m and 4.0 m. The potential for override was increased when the roll angle of the vehicle was positive (e.g., roll away from the barrier) at the time of impact with the guardrail. When the roll angle of the vehicle was negative (e.g., roll toward the barrier) at the time of impact with the guardrail, rollover became a likely outcome.

At impact speeds of 70 km/hr into curb-guardrail systems at offset distances of 2.5 and 4.0 m there was very little probability of barrier override, however, occupant ride down accelerations during redirection was relatively high and in one case involving the 100-mm AASHTO type G curb the longitudinal occupant ride down accelerations exceeded the maximum value of 20 G's allowed in NCHRP Report 350. At the intermediate speed of 85 km/hr the results from the finite element simulations indicated that there is potential for a pickup truck to override a standard strong-post w-beam guardrail that is located at

2.5-m offset distance from both 150-mm and 100-mm curbs. At an offset distance of 4 m from curb to barrier the guardrail redirected the vehicle at an impact speed of 85 km/hr. The occupant ride down accelerations of the vehicle during redirection was considered high and the analysis involving the AASHTO type B curb resulted in excessive occupant ridedown accelerations (i.e., greater than 20 G's).

7.4 Summary

Regarding high-speed roadways with operating speeds greater than 85 km/hr, the curb-guardrail impact studies indicate that installing curbs in combination with strong-post w-beam guardrails is risky. However, if there are no other alternatives, a low profile curb similar to the 100-mm New York curb should be used and it must be placed underneath the guardrail behind the face of the rail element (e.g., w-beam, thrie-beam, etc.). It may also be necessary to strengthen the rail to prevent rupture due to increased tensile forces in the w-beam during impact with such a system. One method of strengthening the rail that was documented in the literature involved nesting w-beam rail elements, however, it is important to note that this may aversely affect the strength of the rail-to-post connection. Another method documented in the literature involved using thrie-beam guardrail systems installed in conjunction with a curb. This worked well for high speed impact with a large car sedan but it has never been tested with a pickup truck – to the knowledge of the author. Other methods of strengthening the guardrail that have proven successful in full-scale crash tests include attaching a rail element to the back of the posts or installing a rub rail.

Regarding low- to moderate-speed roadways with operating speeds less than 80 km/hr curb-guardrail combinations involving curb heights of 150 mm or less with the curbs placed underneath the guardrail behind the face of the w-beam were considered safe and effective. There is potential for a pickup truck to override a standard strong-post w-beam guardrail that is located at 2.5-m offset distance from both 150-mm and 100-mm curbs for impact speeds of 85 km/hr, however, the guardrail redirected the vehicle at offset distances of 4 m. Also, according to the results of the finite element simulations occupant risk increases due to higher ridedown accelerations when the guardrail is offset from the curb and in many cases the occupant ridedown accelerations exceeded the allowable limit of 20 G's.

VIII. GUIDELINES

8.1 Introduction

The guidelines for the use and installation of curbs and curb-barrier combinations presented in this chapter are based on a synthesis of the research conducted in this study and on information from prior studies documented in the literature review in chapter 2.

8.2 Guidelines for Using Curbs on High-Speed Roadways

The use of curbs on roadways with operating speeds greater than 80 km/hr are discouraged, and alternative means should be considered for providing basic curb functions along the roadside such as drainage control and delineation. Curbs constitute a discontinuity along the roadside that may lead to loss of control of a vehicle under certain impact conditions.

Tracking impacts with curbs are not likely to result in serious injury unless a secondary object is struck behind the curb. When a vehicle leaves the roadway in a non-tracking manner, however, wheel contact with a curb could cause the vehicle to trip and overturn. Even so, based on the results of various studies identified in the literature review, it is difficult to discern whether or not curbs are of any greater hazzard than a simple soil-and-sod roadside. Vehicle rollover is believed to occur in only a very small percentage of all curb related accidents, however, the severity of rollovers (e.g., which often result in fatalities) warrants a more in depth analysis of curb design. The analysis of non-tracking impacts with curbs will be addressed in future work in NCHRP Project 22-17.

The following guidelines should be considered tentative until the hazards associated with curbs can be more clearly defined.

For roadways with operating speeds greater than 60 km/hr it is recommended that curb heights should not exceed 100 mm and that the slope of the curb face be 1:3 or flatter so that vehicle accelerations will be minimized while traversing the curb. However, the results of the curb impact study presented in this dissertation, as well as the prior studies identified in the literature review, indicate that curbs with heights 150 mm or less, regardless of the slope of the curb face, pose no significant hazard to encroaching vehicles unless there are secondary objects for the vehicle to encounter in the area behind the curb. The only objects within the clear zone along the roadside should be those that satisfy the safety requirements of NCHRP Report 350. If the secondary object is a guardrail then refer to section 8.3 below to identify proper curb type and placement. When other roadside devices, such as road signs and breakaway poles, are to be used with curbs they should be located as far from traffic as possible. If extensive use of a particular roadside device is to be used with curbing, then computer simulation or full-scale crash testing should be used to ensure that there are no undue hazards associated with such a combination.

8.3 Guidelines for Using Curb-Barrier Combinations on High-Speed Roadways

When curbs are used in conjunction with a roadside safety barrier, the barrier must have adequate strength performance in order to resist excessive lateral dynamic deflections, thus minimizing the risk of a vehicle mounting the curb during impact. The barrier system should, at a minimum, have the strength performance of a strong-post guardrail system such as the modified G4(1S) with wood blockouts, the G4(2W), a thrie-beam guardrail system or similar.

8.3.1 Moderate-Speed Roadways (60 - 80 km/hr)

Any type of sloping curb similar to those listed in the AASHTO Green Book (refer to Figure 1.1) with heights equal to or less than 150 mm placed underneath the guardrail behind the face of the rail element can be used safely in combination with strong-post guardrail systems along roadways with operating speeds of 60 to 80 km/hr.

The most desirable location for curb placement is underneath the guardrail behind the face of the rail element, however, along roadways with operating speeds of 70 km/hr or less the barrier may be positioned at a lateral offset distance of 2.5 m or greater behind the curb for curbs with a height of 150 mm or less. When it is necessary to offset a guardrail behind a curb along roadways with operating speeds ranging from 70 km/hr to 80 km/hr, the curb may be placed underneath the guardrail behind the face of the rail element or the barrier must be positioned at a lateral offset distance of 4.0 m or greater behind a curb and the curb height must not exceed 100 mm.

8.3.2 High-Speed Roadways (over 80 km/hr)

The barrier should not be offset from a curb when curb-barrier combinations are used on roadways with operating speeds greater than 80 km/hr and, further, the use of curbs are discouraged along high-speed roadways with operating speeds greater than 85 km/hr.

When operating speeds are between 80 and 85 km/hr any type of sloping curb similar to those listed in the AASHTO Green Book with heights equal to or less than 150 mm can be used safely with strong-post guardrail systems with the curb placed underneath the guardrail behind the face of the rail element.

When operating speeds are between 85 and 100 km/hr it may be hazardous to install curbs in combination with roadside safety barriers, however, if a curb-barrier system is warranted, the curb should be no higher than 100 mm above the road surface with the curb face having a slope of 1:3 or flatter. It is also recommended that the modified G4(1S) guardrail with wood blockouts not be used unless it is properly modified to increase tensile capacity of the rail element in order to prevent guardrail rupture.

When operating speeds are in excess of 100 km/hr curbs should not be used in combination with roadside safety barriers and other means should be sought to carry out the primary functions of the curb.

A summary of the design guidelines for the use of curb-guardrail combinations along roadways with operating speeds greater than 60 km/hr is presented below in Table 8.1 and in Figure 8.1. The offset distance parameter in Figure 8.1 represents the lateral distance measured from the face of the curb to the face of the guardrail. An offset distance of zero or less in the figure indicates that the curb face should be positioned at or behind the face of the guardrail barrier.

Table 8.1: Design guidelines for the use of curbs along roadways with operating speeds greater than 60 km/hr.

Operating Speed (km/hr)	**Sloped Curb Types**	**Curb-Barrier Placement**
60 - 70	150-mm or smaller	under guardrail behind rail element
	150-mm or smaller	barrier should be offset 2.5 m or greater from curb
70 - 80	150-mm or smaller	under guardrail behind rail element
	100-mm or smaller	barrier should be offset 4 m or greater from curb
80 - 85	150-mm or smaller	under guardrail behind rail element
85 - 90	100-mm or smaller	under guardrail behind rail element
90 - 100	100-mm or smaller with slope of curb face 1:3 or flatter	under guardrail[ƒ] behind rail element
> 100	Curbs should not be used in combination with safety barriers	

ƒ The G4(1S) guardrail with wood blockouts should not be used unless it is properly modified to increase tensile capacity of the rail element **(REF)**

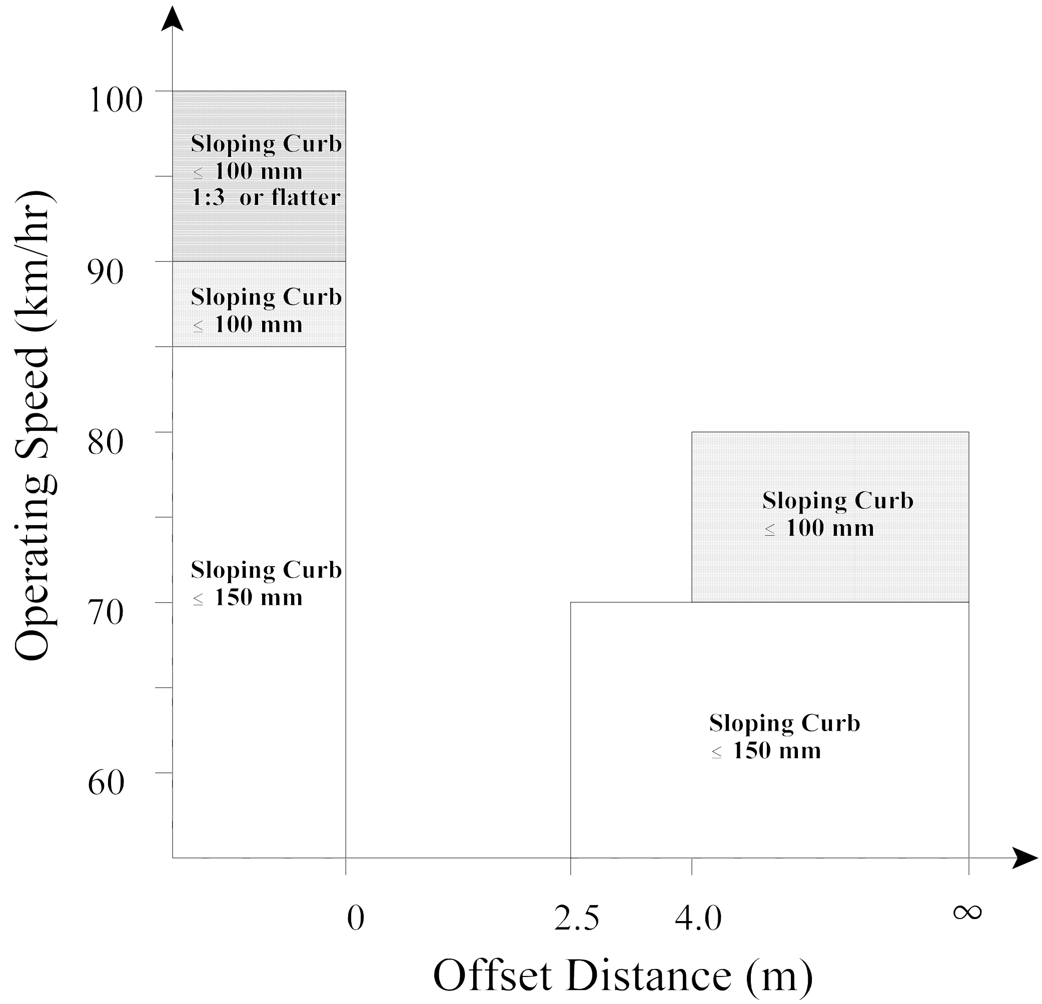

Figure 8.1: Chart illustrating the design guidelines for the use of curbs along roadways with operating speeds greater than 60 km/hr.

IX. SUMMARY AND CONCLUSIONS

9.1 Introduction

The results of the studies identified in the literature and the results of the parametric analyses conducted in this research were synthesized in order to develop a general set of guidelines for the design and installation of curbs and curb-barrier systems along roadways with operating speeds greater than 60 km/hr. The guidelines are based on the results of both computer simulation and full-scale crash tests. The study involved the analysis of vehicles traversing several commonly used curb types under a variety of impact conditions, as well as, the analysis of vehicle impact into various curb-guardrail combinations. The research presented herein identified common types of curbs that could be used safely and effectively on high-speed roadways and also identified the proper combination and placement of curbs and barriers that would allow the traffic barriers to be effective, i.e. safely contain and redirect an impacting vehicle.

9.2 Summary of Previous Research Studies

An in-depth review of published literature was conducted in order to identify information pertinent to the design, safety and function of curbs and curb/barrier combinations. The studies that were found in the literature used a variety of vehicle types including small cars, large cars and pickup trucks. It was found that both the large and small cars crossing curbs less than150 mm high in a tracking manner are not likely to cause the driver to loose control of the vehicle or cause the vehicle to become unstable, unless a secondary impact occurs. The dynamic response of a pickup truck crossing over curbs, however, had never been evaluated in previous studies with either full-scale tests or computer simulation and was thus unknown.

Errant vehicles leave the roadway in a variety of orientations, however, it is assumed that the majority of these vehicles encroach onto the roadside in a semi-controlled tracking manner. In such cases, the left or right front bumper would be the first point of contact with a roadside object in an impact event. The position of the bumper upon impact has, therefore, been a primary concern involving impacts with longitudinal traffic barriers, where it has been assumed that the position of the bumper during impact is a reasonable indicator of vehicle vaulting or underriding the barrier.

The conclusions from these earlier tests and analyses were in general agreement that curbs in front of the guardrail could cause vaulting. If curbs were required for drainage purposes the only alternative was to place the curb behind the face of the barrier. This arrangement shields the curb from the impact while allowing the curb to channel runoff water from the roadway. The idea was to locate the curb such that minimal interaction between the vehicle and curb occurred. This worked well with lighter vehicles such as the 820-kg small car, but did not prevent vehicle-curb interaction for the larger cars which have a mass of over 2000 kg, unless the guardrail was retrofit in some manner to strengthen it and minimize guardrail deflection. To circumvent the problem, one option that was considered was to use a low profile curb underneath the guardrail in order to minimize the effects that the curb would have on vehicle trajectory if the wheels of the vehicle managed to make contact with the curb during impact.

Tests were conducted by various organizations in which a low profile curb was placed behind the face of the guardrail. This design proved successful in tests with the larger cars, while tests involving pickup trucks resulted in success in some cases and failure in others. In cases where the test was a failure, it was not clear whether the failure was induced by vehicle-curb interaction or if it was simply caused by inadequate barrier performance. It was apparent, however, that curb-barrier systems pose a much greater hazard to pickup trucks in high-speed impacts than they do to cars, and also that much more information regarding pickup impact into curb-barrier systems was warranted.

9.3 Summary of Current Research

Finite element analysis was used in this research to conduct a parametric investigation involving a 2000-kg pickup truck impacting various curbs and curb-barrier combinations to determine which types of curbs are safe to use on high-speed roadways and to determine proper placement of a barrier with respect to curbing such that the barrier remains effective in safely containing and redirecting an impacting vehicle. The curb types used in the study included the 150-mm AASHTO type A, the 150-mm AASHTO type B, the 150-mm AASHTO type D, the 100-mm AASHTO type C, the 100-mm AASHTO type G and the 100-mm New York curb. The longitudinal safety barrier used in the study was the modified G4(1S) guardrail with wood blockouts, which is one of the most widely used guardrails in the U.S.

Each component of the guardrail model was validated both quantitatively and qualitatively with laboratory tests, with the exception of the anchor system for which no test data was available. The modified NCAC C2500R (reduced element) pickup truck model (i.e., model with modifications made to the suspension system by WPI) was used to simulate the impact of a 2000-kg pickup truck. The NCAC C2500R model has been widely used in previous studies to analyze vehicle impact into roadside barriers and therefore the model has been generally debugged.

The accuracy of the models' results were quantified prior to being used in this study. The models were first used to simulate a 2000-kg pickup impacting the modified G4(1S) guardrail at 100 km/hr at an angle of 25 degrees. The results were validated by comparing them to results obtained from a full-scale crash test documented in the literature, and it was concluded that the models provide realistic behavior of both the guardrail and vehicle in such an impact event.

The validated models were then used in a parametric analysis to investigate the effects of various curb types in tracking impacts with a 2000-kg pickup truck on the stability and trajectory of the vehicle during simple curb traversals. The parametric analysis involved six curb types (i.e., AASHTO types A, B, C, D and G and the 100-mm New York curb), two impact speeds (i.e., 70 and 100 km/hr) and three impact angles (i.e., 5, 15 and 25 degrees).

The models were also used in a parametric study to investigate the crashworthiness of curb-barrier combinations in tracking impacts with the 2000-kg pickup truck. The parametric analysis involved the modified NCAC C2500R pickup truck model impacting the modified G4(1S) guardrail model at impact speeds of 70, 85 and 100 km/hr, at an impact angle of 25 degrees and at offset distances from curb to barrier of 0, 2.5 and 4 m.

The results of the curb traversal study indicated that the stability of the pickup truck would not be compromised in tracking impacts, however, the trajectory of the front bumper was sufficient to imply a risk of barrier override when a standard strong-post guardrail is placed anywhere from 0.5 m to 7.0 m behind 150 mm high curbs or 0.6 m to 7.0 m behind 100 mm high curbs.

The finite element results of the pickup truck model impacting various curb-guardrail combinations confirmed that the presence of curbs are potentially hazardous. The results of the parametric study were used to identify certain combinations that were more likely to result in acceptable, as well as, unacceptable barrier performance, and a table defining proper curb type and barrier placement was presented. It should be noted that even those cases that were identified as being successful resulted in poorer performance of the guardrail and a higher risk of injury for the occupants of the vehicle than was the case when the curb was not present.

9.4 Future Research

While the foregoing dissertation provided a considerable amount of information regarding the effects of curbs along high-speed roadways there is still a great deal of information needed in order to develop a more complete set of guidelines for the use and installation of curbs. The issue of non-tracking impacts with curbs needs further attention, full-scale tests are needed to confirm computer simulation predictions and an in depth review of crash data bases is needed to develop a more clear understanding of extent of the curb related safety problem in the real world.

Finite element analysis is one method that may be useful in the study of non-tracking impacts with curbs. The lack of detail in the model of the wheel assembly on the vehicle models, however, may greatly affect the accuracy of their results in simulating the response of lateral loading on the wheels (e.g., failure of wheel assembly components) during non-tracking impacts. It is therefore recommended that full-scale testing be used to investigate such an event, however, it is realized that conducting full-scale non-tracking tests under impact conditions representing real life conditions are difficult to achieve without the aid of a live driver.

The advantage of full-scale crash tests is that they are actual physical impact events where there is little ambiguity about the results. The disadvantage is that they are costly, and it is seldom feasible to perform very many tests so the testing results usually do not address a very wide range of conditions. Some full-scale tests should be conducted to validate the results of the computer simulation analyses. For example, select cases of curb-barrier systems identified in the computer simulation study for which failure or success of the system would be expected, should be crash tested in order to verify the computer predictions. If the full-scale tests confirm that the computer simulation results are accurate then the results of the many computer simulated impacts in the parametric analysis can be considered a reasonable estimate of performance of the various curb-barrier systems and, thus, would strengthen the conclusions made in this dissertation.

Currently, as part of NCHRP project 22-17, researchers at Bellomo-McGee, Inc. are conducting a study of existing crash/geometric databases in order to characterize the extent and severity of safety problems associated with curb and curb-barrier combinations on high-speeds roadways. That study is almost complete and when the final results are available they will be incorporated with the current data which will further aid in the development of the design guidelines being developed by researchers at Worcester Polytechnic Institute for NCHRP Project 22-17.

X. REFERENCES

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