



Safety Performance of Concrete Median Barriers under Updated Crashworthiness Criteria

Elham Sahraei Esfahani

Dhafer Marzougui

National Crash Analysis Center, The George Washington University
20101 Academic Way, Ashburn VA 20147 USA

Email: dmarzoug@ncac.gwu.edu

Email: cdkan@ncac.gwu.edu

Kenneth S. Opiela

Turner Fairbank Highway Research Center
Federal Highway Administration, USDOT
6300 Georgetown Pike, McLean VA 22101-2296 USA

Email: Kenneth.opiela@fhwa.dot.gov

This working paper is a compilation of recent efforts and findings intended to solicit feedback on the approach, scenarios analyzed, findings, interpretations, conclusions, and implications for practice resulting from the efforts of the research team. Please forward comments or questions to the authors noted above. These efforts will ultimately be documented and made available to advance research efforts related to this topic and guidance for practice.

ABSTRACT

The safety performance of concrete median barriers (CMB) was investigated using non-linear finite element crash simulations. The investigation was motivated by concerns over the viability of commonly used CMB designs under the proposed update to the national crashworthiness standards, particularly the Test Level 4 requirements for longitudinal barriers. The analysis focused on procedures for Test 4-12 from National Cooperative Highway Research Program (NCHRP) report 350, and the update of it. Test 4-12 involves impacts of a single unit truck (SUT) into the longitudinal barrier. This effort was undertaken to study the effects of various factors in crash performance for CMBs to assess alternative criteria and identify design retrofit options. A modeling and crash simulation analysis approach was seen as a cost efficient method to consider various alternatives. LS-DYNA was used to execute a series of crash simulations using finite element models of an SUT and various CMB designs. The basic models were validated using full-scale crash test results. Simulations were performed to study the effect of vehicle weight (8, 10, and 12 tons), impact speed (80, 90, and 100 km/hr), barrier height (32, 37, and 42 in), barrier shape (New Jersey and F- shapes), and side-wall friction on crash performance. The results showed that vehicle speed and barrier height are the two most important factors in performance of CMBs. The effects of friction and barrier shape were less significant.

Safety Performance Evaluation of Concrete Median Barriers under Updated Crashworthiness Criteria

INTRODUCTION

Concrete safety shape barriers or concrete median barriers (CMB) are one of the most commonly used types of median barriers on highways of United States. These barriers are designed to minimize the crossover of vehicles into on-coming traffic on divided highways. CMBs are rigid barriers which do not deflect even under severe crash conditions, but they can be highly effective in reducing the potential for crossovers even when the opposing traffic is in close proximity. Researchers have evaluated their performance using crash tests, computer simulations, and in-service performance evaluation (1,2,3). However, most of this research focused on evaluating crash performance with passenger cars or light trucks, as these barriers were not originally designed for impacts involving large trucks or other heavy vehicles (1).

Since 1993, the National Cooperative Highway Research Program (NCHRP) Report 350 has served as the national standard for the crashworthiness of roadside features. CMBs were subject to the procedures for longitudinal barriers at varying test levels. Under NCHRP 350, a CMB could be considered acceptable for use on the National Highway System at Test Level 4 if the barrier was demonstrated to pass tests 4-10 through 4-12. These test involved a small car (820 kg) and a pick-up truck (2,000 kg) at 100 km/h and 20 degrees and a single unit truck (SUT) at 8,000 kg at 80 km/hr and 15 degrees (4). Since 2001, efforts have been underway to develop and disseminate a newer set of crashworthiness procedures and evaluation criteria. One notable proposed change for Test Level 4 is to increase the weight of the single unit truck to 10,000 kg and increase the speed to 90 km/h. These changes increase the energy in the crash for Test 4-12 and subsequently it has raised concerns that the 32 inch variety of the CMB would not pass the tests under the proposed update to NCHRP(5).

This effort was initiated to evaluate safety performance at test level 4 for varying conditions to help define a reasonable update to the standard crashworthiness procedures and identify possible design retrofit options for CMBs. A full-scale crash test of a permanent New Jersey safety shape barrier was conducted according to update to NCHRP Test 4-12 by the Midwest Roadside Safety Facility (MwRSF) has shown that the barrier did not fulfill the requirements defined in the proposed update (6). This research was aimed to evaluate what factors are the most important in determining the crash behavior of CMBs. For this purpose LS Dyna non-linear finite element software was used to simulate crash events for Test 4-12. The simulation model was first validated against available crash test results. In the subsequent analyses several factors believed to influence crash performance were varied including vehicle weight, impact speed, side wall friction, barrier height, and barrier shape.

FINITE ELEMENT MODEL OF THE VEHICLE

The vehicle model used for this study was the non-linear finite element model of a single unit truck (SUT) developed by the National Crash Analysis Center (NCAC) that included 155 parts, and 35,400 elements (33,861 shell elements, 548 beam elements, and 886 solid elements). An elastic cube mass was added to represent the load or ballast to achieve the prescribed SUT weight required for Test 4-12 under NCHRP 350 and the proposed update. This SUT model had been used in many previous simulation studies and had performed well.

A comparison of the characteristics of the SUT compared to one crash tested at the MwRSF are presented in Table 1. Figure 1 provides the legend for the vehicle geometry referenced in the table.

Initially, the SUT model was given ballast to bring its weight to 10,000 kg; center of gravity of the ballast was 1650 mm from ground based on proposed update to NCHRP 350. After validating the FE model against the MwRSF crash test, the mass was adjusted to examine effect of vehicle weight on crash performance of barrier. Vehicle weights examined include 8,000 kg, 10,000 kg, and 12,000 kg. Also center of gravity of ballast was adjusted to 1750mm, and 1600 mm in select simulations either to comply with original NCHRP 350 report requirements or to evaluate its possible effect on the results of crash. To represent the impact speed of the vehicle linear initial velocity was applied to all parts of the model, and equivalent angular velocities were applied to the tires to represent their rotation. This rotational velocity is very important to realistically simulate the interaction between the barrier and tires of the vehicle.

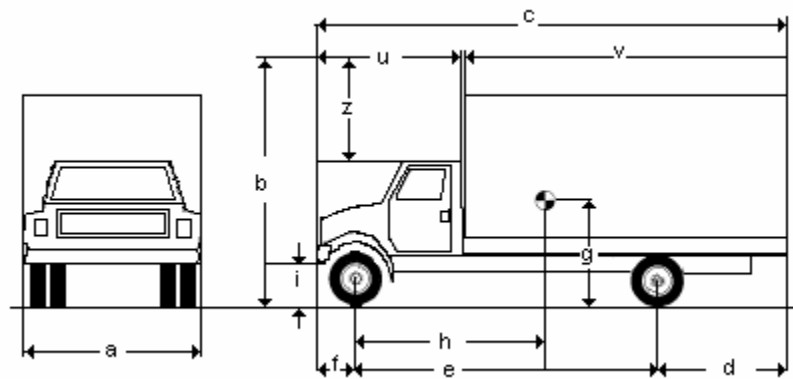


FIGURE 1 Vehicle Geometry

TABLE 1 Test Vehicle Versus FE Model Geometry (all dimensions in mm)

	Vehicle geometry	Test Vehicle	FE model
a	front bumper Width	2375	2392
b	overall height	3515	3318
c	overall length	8299	8491
d	rear overhang	2654	2388
e	wheel base	4775	5287
f	front overhang	838	846
g	C.G height	1351	1332
h	C.G horizontal Distance	3325	3235
i	Front bumper Bottom.	533	538
u	cab length	2610	2587
v	Flat bed or box length	5613	5747
z	roof height difference	1270	1117

BARRIER MODELS

New Jersey safety shape barrier model and F-shape barrier models developed in National Crash Analysis Center were used for these simulations. For the validation phase the New Jersey barrier with height of 32 inch was used. For further evaluations New Jersey barriers with heights of 37 in.

and 42 in. plus F-shape barriers with heights of 32 in., 37 in., and 42 in. were examined in simulations.

As concrete safety shape barriers do not deform or deflect even under sever crash conditions, all barrier models include only rigid shell elements. For the simulations, the length of barriers was extended to 41,222 mm to make sure vehicle does not reach to the end of barrier before the end of the simulation.

Barrier model mesh was refined to sizes between 50 mm to 93 mm to ensure optimum contact between vehicle parts and barrier with out excessive penetrations. Lower surface of barriers were fixed to prevent any movement or deformation in the barrier during the crash simulation.

INITIAL SIMULATION SET UP AND VALIDATION PHASE

For the validation phase of this study, the initial model was set-up according to the procedures for update to NCHRP Test 4-12. The SUT vehicle weight was 10,000kg (including ballast weight), impact speed was 90 km/h, and the impact angle was 15 degrees. The CMB used was the 32 in high New Jersey barrier model. There were two full-scale crash tests available with similar set-ups - one from MwRSF and the other from the Texas Transportation Institute (TTI) (6,7). Figure 2 shows roll, and yaw angles of MwRSF crash test compared to the FE simulation. The MwRSF test vehicle was a 9,999 kg single unit truck, and the test speed and impact angle were 90.9 km/h and 16.2 degrees. It can be noted that the roll and yaw angle results are similar with some of the differences explained by the slightly higher speed and impact angle in the crash test. Figure 3 shows longitudinal velocities from the MwRSF SUT crash test and the FE simulation.

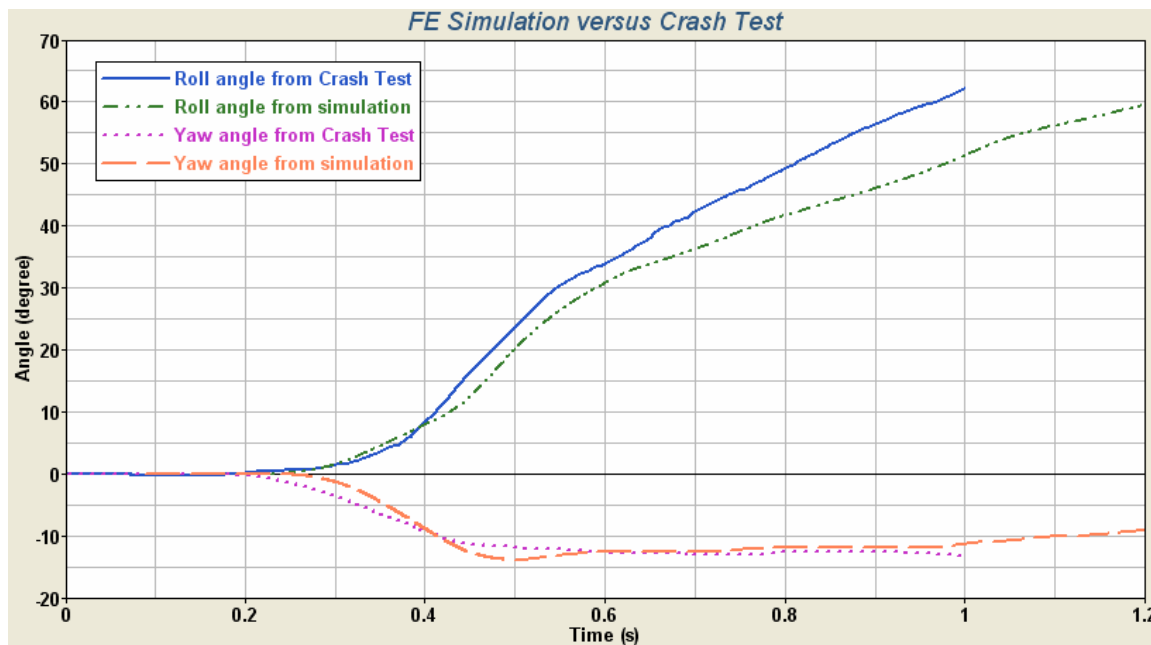


FIGURE 2 Comparison of Roll and Yaw Angles from MwRSF Crash Test and FE Simulation (For Set Up According To update to NCHRP Test 4-12)

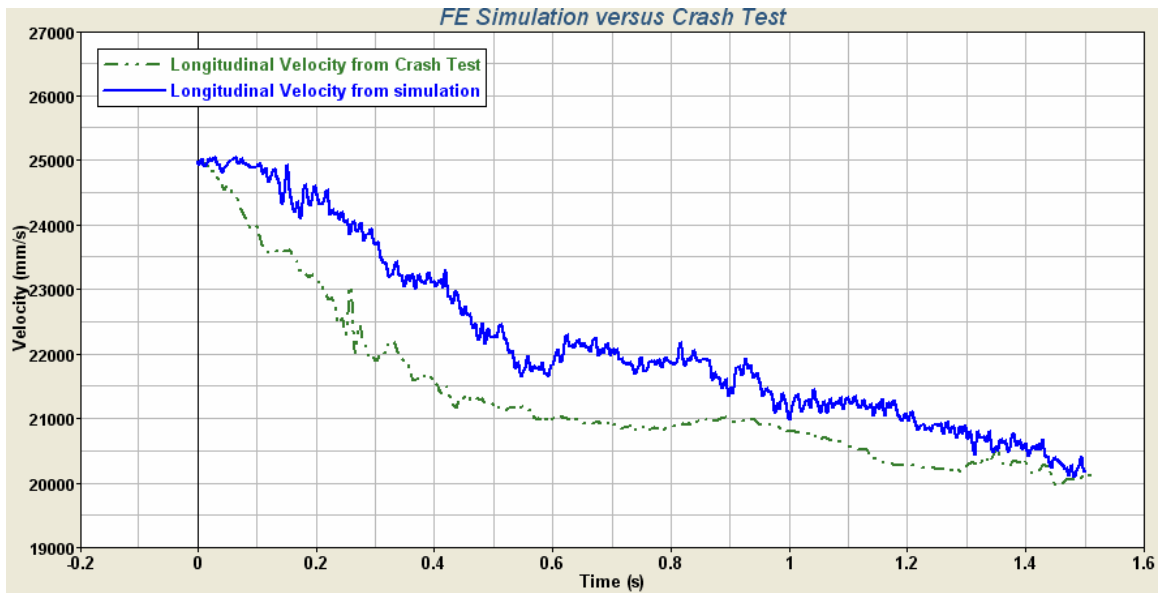


FIGURE 3 Longitudinal Velocity Of The SUT From FE Simulation And Crash Test (Set Up According To Test Level 4-12 Of The Update To NCHRP 350)

Figure 4 shows pictorially the test and simulation model responses during the crash. These test pictures are from crash test conducted at TTI in which the test vehicle mass was 10,020 kg, closing speed 92.3 km/h, and angle 15 degrees (7). In the FE simulation and crash test, three phases during vehicle impact to barrier can be noted, In the first phase, front bumper of the vehicle comes in contact with the barrier and begins to deform while right front tire climbs the lower slope of New Jersey barrier. In the second phase of the impact, the right front tire returns to the ground while the right front side of the cab ride along the barrier, and the vehicle begins to redirect and roll. In the last phase, the box comes in contact with top of barrier, and the roll of the box around the contact point increases while whole vehicle slides on the top of the barrier, and finally whole vehicle rolls until it is on its side on the ground. These three phases can be recognized in Figure 4.

Both simulation and test results showed that the 32 in. New Jersey safety shape barrier does not meet the structural adequacy requirements of update to NCHRP. The guidance stated in the evaluation criteria says the barrier "...should contain and redirect the vehicle or bring the vehicle to a controlled stop; and the vehicle should not penetrate, underide or override the installation..." In this case override (i.e., rollover) of the vehicle to the other side of barrier violates the structural adequacy requirement. Occupant risk evaluation criteria suggests that "It is preferable, although not essential, that the vehicle remain upright during and after collision." As mentioned, the vehicle rolled onto its side, which while acceptable, is not the preferred crash performance.



FIGURE 4 Left: Crash Performance Response of the FE Simulations Compared to the Full-Scale Crash Test (for update to NCHRP Test 4-12)

ANALYSIS OF NCHRP 350 CRASH PERFORMANCE

The analysis of the factors involved in SUT crashes with CMBs (and as a validation benchmark) continued with the simulation of a crash test based on the original NCHRP 350 requirements (4). For this simulation the weight of the SUT (and its ballast) was reduced to make the total vehicle mass 8,000 kg, and the vehicle speed reduced to 80 km/h, also center of gravity of the ballast was adjusted to 1750 mm to comply by requirements of original NCHRP350. The impact angle did not change from 15 degrees used in the previous simulation. In this crash simulation the first and second phase of contact was similar to the previous simulation, however during the last phase when box hit top of the barrier vehicle stopped rolling counter clockwise, and after sliding for a while began a reverse roll which made the vehicle to come back to upright position again. Figure 5 depicts these three phases of the simulation. This simulation verified that the New Jersey safety shape barrier performance satisfies the requirement of the previous NCHRP 350 test requirement.

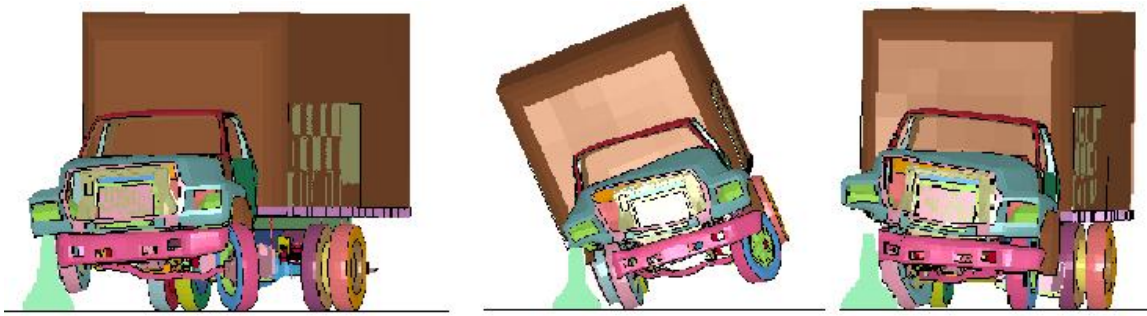


FIGURE 5 Three Phases of Impact for Crash Simulation Based On NCHRP 350 (1993)

Figure 6 shows roll and yaw angles of the SUT during this simulation, comparing these results with Figure 2 reveals the difference in barrier performance in the two crashes. In Figure 6 the roll angle stops increasing at about 30 degrees at 0.75 seconds into the crash event and then begins to decrease at 0.9 second, and finally reaches the zero roll angle or upright position before end of simulation. In Figure 2 the roll angle does not stop increasing at any point.

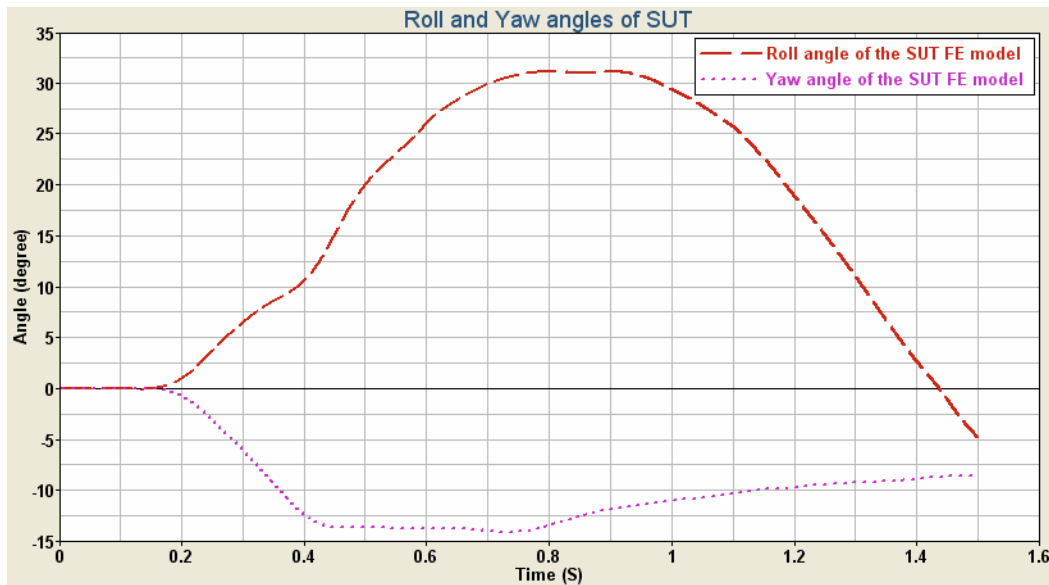


FIGURE 6 Simulated Roll And Yaw Angles of the SUT Based On NCHRP 350 (1993)

WEIGHT AND SPEED FACTOR EFFECTS

In previous section, it was observed that either weight increase or the increase in the impact speed of the vehicle over the criterion in NCHRP 350 for Test 4-12 results in the CMB being unable to prevent the vehicle override thus failing to provide acceptable performance. In this section, the focus is to identify which factors are the main causes of the override (i.e., rollover). Four additional simulations were undertaken to reflect effect of varying vehicle weight, and impact speed. In the first two simulations vehicle weight was increased to 10,000 kg in one simulation and 12,000 kg in other one while keeping the impact speed at 80 km/h and the impact angle at 15 degrees.

In these simulations with increased weight for impacts at 80 km/h, the barrier was able to redirect the vehicle without rollover, although maximum roll angle increased to 40 and 45 degrees respectively, and return to upright position was delayed relative to that for the 8,000 kg SUT. Figure 7 shows roll

angle of the SUT for three vehicle masses simulated. These results show the increase in mass of the test vehicle alone can not be the cause of failed performance of barrier in the updated test. Therefore, the next two simulations were focused on studying effect of speed increases.

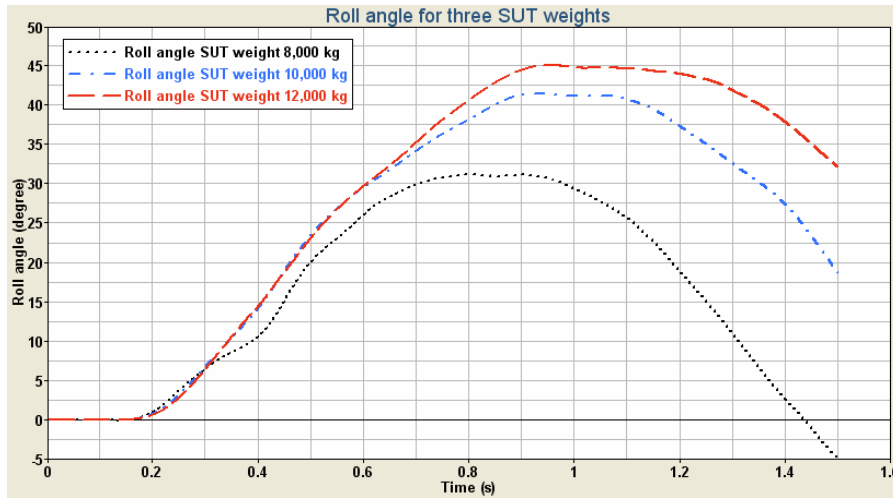


FIGURE 7 Comparison of Roll Angles for SUT in Crash Events at Varying Vehicle Masses for Impact Speed of 80 km/h, and Impact Angle of 15 Degrees

In next two simulations, the vehicle weight was kept constant at the 8,000 kg level specified in NCHRP 350 (1993), but the impact speed was increased to 90 km/h and 100 km/h respectively. Results of these two simulations show that increasing speed to 90 km/h even with 8,000 kg vehicle makes the barrier performance marginal, and increasing the speed to 100 km/h makes the failure of barrier in preventing turnover imminent.

Table 2 provides a tabular summary of CMB crash performance relative to varying impact speeds and SUT vehicle weights. The results suggest a problem for the 32 in. New Jersey CMB under the updated criteria. Three of the situations were not evaluated (as noted) because the outcomes were expected to be failures.

TABLE 2 Table Showing Summary of Crash Performance Outcomes for Varying SUT Vehicle Weights and Impact Speeds

Impact Speed	SUT Vehicle Weight (with Ballast)		
	8,000 kg	10,000 kg	12,000 kg
100 km/h	Fail (Update to NCHRP)	Not evaluated	Not evaluated
90 km/h	Marginal (Update to NCHRP)	Fail (Update to NCHRP)	Not evaluated
80 km/h	Pass (NCHRP 350)	Pass (Update to NCHRP)	Pass (Update to NCHRP)

BARRIER HEIGHT EFFECT

As it was verified that the 32 in. New Jersey barrier does not satisfy the Test 4-12 of the proposed update to NCHRP, an attempt was done to find out what changes can improve barrier performance to fulfill the requirement. In the first step, the height of the New Jersey barrier was increased to 37 in. and 42 in. and evaluated using simulation according to the Test 4-12 procedure.

A simulation with a 10,000 kg vehicle impacting the barrier with impact speed of 90 km/h, at angle of 15 degrees, to a New Jersey barrier of 37 inch showed that barrier can keep the maximum roll below 40 degrees, and vehicle will begin to roll back to an upright position after 1 second. However, vehicle did not reach the zero roll in the 1.4 second simulation of the crash event. A New Jersey barrier 42 in. high was able to stop rolling at about a roll angle of 30 degrees at 0.6 seconds into the crash event and successfully return the vehicle to upright position during simulation. Figure 8 shows the roll angle results for the SUT from these crash simulations.

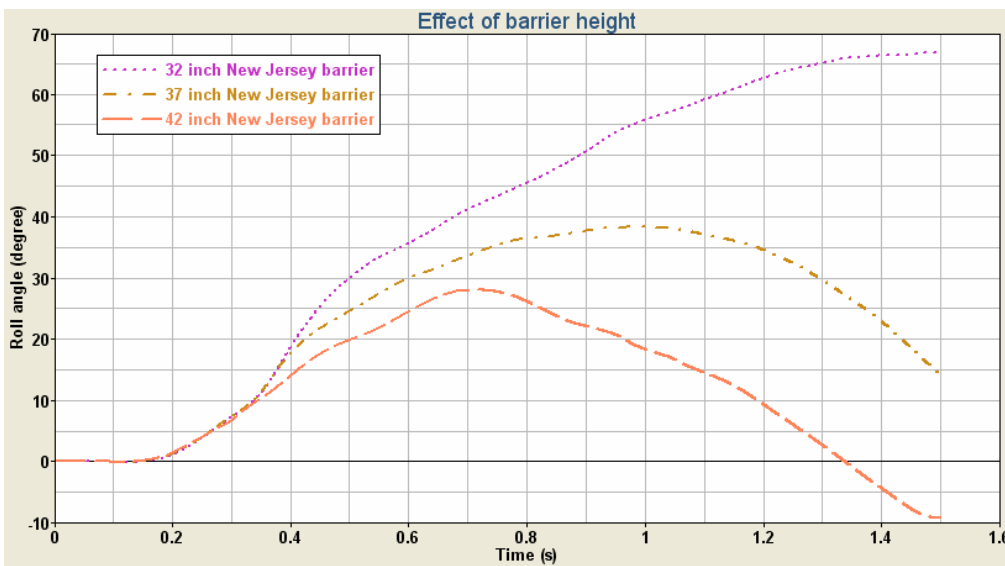


FIGURE 8 Changes in Roll Angle with Increasing Barrier Height

BARRIER SHAPE EFFECT

Similarly, the F-shape barrier was tested to evaluate its performance in redirecting SUT for update to NCHRP Test 4-12. The 32 inch F-shape barrier showed no significant difference in performance compared to the New Jersey barrier of same height, both failed to successfully redirect the vehicle and prevent override. F-shape barrier of 37 inch height showed a similar behavior to 37 inch New Jersey barrier, which led to the vehicle beginning to roll in the reverse direction during the last part of the simulation. However, vehicle did not reach zero roll or come back to upright position during simulation. The 42 inch high F-shape barrier performed similar to the 42 inch New Jersey barrier and had satisfactory performance. The barrier stopped the rolling of vehicle below 20 degrees at about 0.6 seconds, and induced the vehicle to go back to the upright position during simulation (Figure 9).

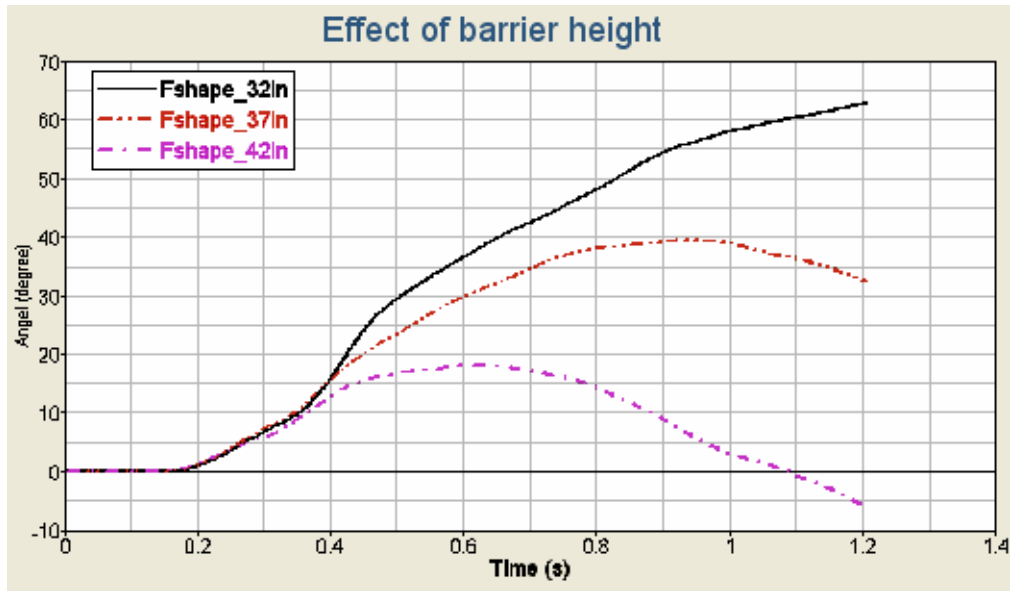


FIGURE 9 Comparison of Height Effects for F-Shape Barrier

EFFECT OF FRICTION

Some previous studies have mentioned possible effect of the side friction between the side of the CMB and the side-wall of the vehicle tire as a factor to be considered to limit climb and hence potential for SUT rollovers. There seems to be little established knowledge of the barrier to tire interaction, but it has been suggested that real world crash data shows reduced number of rollovers in adverse weather conditions (e.g., rain, or snow)(1), Therefore, it was decided to attempt an analysis of the effect of friction between barrier and vehicle using simulation. Using the same simulation set up as for the previous simulations, a 10,000 kg SUT vehicle, impact speed of 90 km/h, and impact angle of 15 degrees, a new simulation was conducted varying the coefficient of friction between vehicle and barrier from “0.5” (in previous simulations) to “0”. Results showed that coefficient of friction has minimal effect in roll angle of vehicle, and the barrier failed to prevent rollover in both cases with no significant change (Figure 10). Further study of the interaction between the tire and barrier is needed.

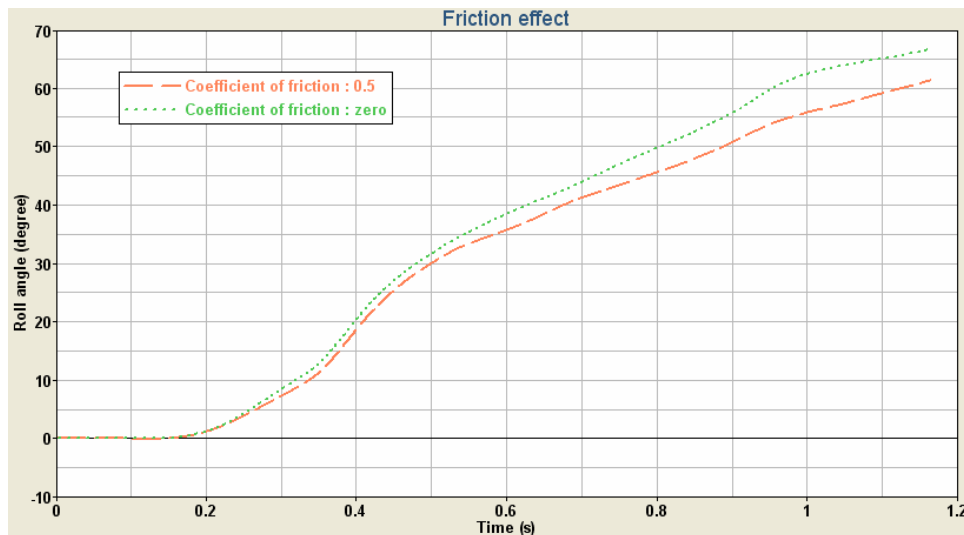


FIGURE 10 Effect of Friction on Roll Angle

CENTER OF GRAVITY OF THE BALLAST

One of the changes in the proposed update to NCHRP350 test requirements is the change in height of center of gravity of the ballast. The original NCHRP 350 requires that height of center of gravity of ballast be in the 1700 (+, - 50) mm range, while the proposed update requires that height of the center of gravity be in 1600 (+, - 50) mm. In the last part of this effort, the effect of change in height of center of gravity in the proposed update to NCHRP 350 was studied. The simulation was set up to replicate Test 4-12 of the proposed update to NCHRP 350 with a vehicle weight 10,000 kg, impact speed 90 km/h, and impact angle of 15 degrees. Varying ballast C.G heights were examined for 1750 mm, 1650 mm, and 1600 mm. Figure 11 depicts the change in the roll angle of the SUT caused by these changes in C.G height of ballast. As can be observed from the figure increasing height of C.G of the ballast from 1650 mm to 1750 mm increases the roll angle of vehicle in time; however reducing the C.G height of ballast to 1600 mm does not make any significant change in rolling angle of the SUT.

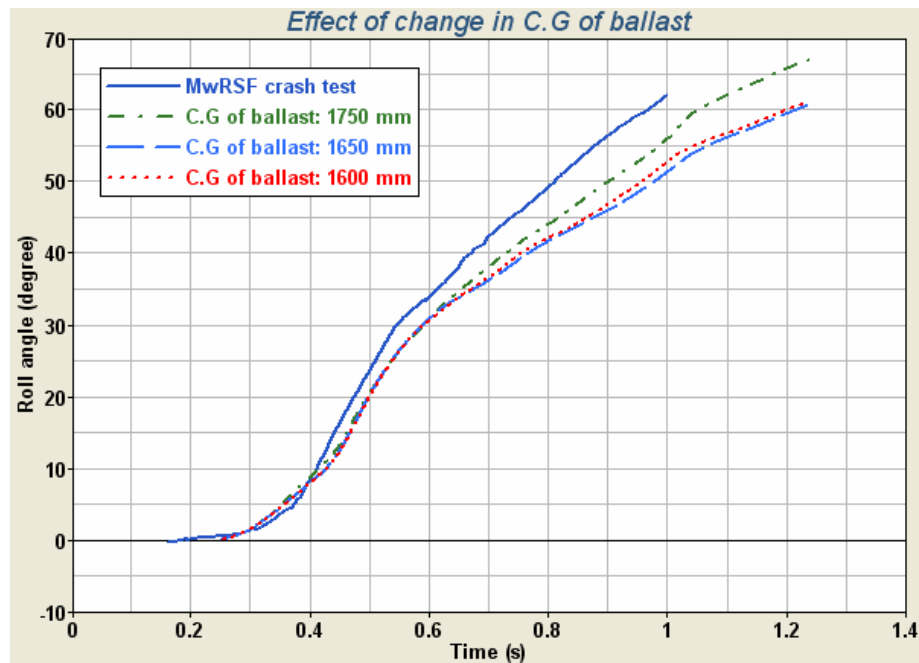


FIGURE 11 Effect of change in C.G of ballast, simulation set up based on proposed update to NCHRP 350

CONCLUSIONS

This study showed that the 32 inch high New Jersey, and F-shape concrete safety shape barriers are not likely to fulfill the requirements for Test 4-12 under the proposed update to NCHRP 350. The crash simulations as well as full-scale crash test results reveals that having single unit truck of 10,000 kg impacting these concrete barriers with speed of 90 km/h at angle of 15 degrees, CMB cannot successfully redirect the SUT and results in override (i.e., rollover). While there has been some mixed testing and simulation results for the NCHRP 350 Test 4-12, simulations conducted in this effort showed positive outcomes. Future testing at a lower speed (i.e., 85 km/h) can lead to positive outcomes for both New Jersey, and F-shaped barriers and both can successfully redirect a 10,000 kg SUT. Also, increasing height of barrier to 42 inch enables both barriers to redirect the

single unit truck successfully, and satisfy the requirements of the update to NCHRP 350. Changing friction between vehicle and barrier was shown to have limited effect and no significant difference in the outcome of the crash, but there is a need for further investigations in this area.

Additional research is planned to look at other barrier shapes, evaluate retrofit designs to increase height, assess the specifics of ballasting (particularly with regard to its center of gravity), and better understand and characterize the side friction effect. These will be reported as they are completed.

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