HEAD AND NECK INJURY POTENTIAL IN INVERTED IMPACT TESTS

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ABSTRACT

NHTSA has concluded that there is a relationship between roof intrusion and the injury risk to belted occupants in rollovers [1]. Roof crush occurs and potentially contributes to serious or fatal occupant injury in 26% of rollovers [2]. The inverted drop test methodology is a test procedure to evaluate the structural integrity of roofs under loadings similar to those seen in real world rollovers. Drop test comparisons have been performed on over 20 pairs of production and reinforced vehicles representing a large spectrum of vehicle types. The structural modifications in the reinforced vehicles maintained the occupant survival space and seat belt geometry. This paper analyzes inverted drop testing performed on several production and reinforced matched vehicles with restrained Hybrid III test dummies. Review of neck load data indicates that reduced roof crush results in a direct reduction in neck load, thereby increasing occupant protection. Restraint loading and performance, relating to roof structure integrity, is also evaluated.

INTRODUCTION

The probability of injury in rollovers is increased with roof crush as shown by Rains [4], Rechnitzer [5], Summers [6] and the U.S. Federal Register [7]. It is estimated that roof intrusion occurs and potentially contributes to serious or fatal occupant injury in approximately 26% of rollovers [8].

Previous testing on many different vehicle types indicates that damage consistent with field rollover accidents can be achieved through inverted drop testing from small drop heights [9]. Drop test comparisons were performed on over 20 pairs of vehicles representing a large spectrum of vehicle types. Each vehicle pair included a production vehicle and a vehicle with a reinforced roof structure dropped under the same test conditions. Several examples of post-production reinforcements to roof structures that significantly increased the crush resistance of the roof were given. The modification methodologies are well-accepted practices in the industry, which have been published in previous research and/or incorporated in production vehicles. The basic approach was to close open-section components, add internal reinforcements and/or void fill components with structural foam or epoxy [10,11,12,13,14]. The results of these modifications indicated that roof crush could be dramatically decreased, as roof crush was reduced by 44 – 96% with only a 1–3.1% increase in vehicle weight.

Previous work by the authors demonstrates that the HYBRID III neck lacks biofidelity in rollovers [15]. The Hybrid III neck has been reported to be up 50 times stiffer than the human neck in compression [16]. Due to its extreme stiffness, the Hybrid III neck holds the dummy head straight up which nearly eliminates flexion and guaranties high neck axial compression loads. The human neck on the other hand, is very flexible, and usually experiences flexion injuries instead of compression injuries. The flexing motion of the head can dramatically increase the available survival space of the occupant [17,18]. The Hybrid III dummy is essentially predisposed to produce significant axial neck injuries well before a human neck would experience flexion injuries. Although the HYBRID III dummy has many limitations, it can still be a useful tool. If the dummy neck does not record an axial neck injury in an inverted drop test, then the likelihood of a flexion injury to a human would be eliminated.

Understanding the known limitations of the Hybrid III, several pairs of dummy-equipped inverted drop tests were conducted to further investigate the relationship between roof crush, survival space and neck injury potential. The dummy axial neck loads were analyzed and compared in each of the drop test pairs.

DROP TESTING COMPARISIONS

The vehicles tested for this paper were inverted and dropped from a predetermined height and orientation based upon damage sustained by similar vehicles in a real world accident scenario. Initial drop conditions used were from 12 – 24 in of height, 16 – 25 degrees of roll angle, and 5 – 7 degrees of pitch angle. The production drop test vehicles sustained roof damage consistent with those sustained by real-world rollover accident vehicles. An equivalent production vehicle was structurally modified based on the deformation patterns and failure modes seen in the corresponding real-world accident vehicles and production drop test vehicles. The modifications were limited to reinforcing the existing structure without significantly impacting the interior compartment or exterior styling. Each reinforced vehicle was then subjected to the same drop test environment as the production vehicle with differences in structural performances as discussed.

Inverted Drop Test Setup

1996 Ford Escort With Hybrid III Dummy - A pair of 1996 Ford Escort passenger cars, each equipped with a test dummy, were subjected to inverted drop tests. One of the cars was a production vehicle and the other vehicle had a reinforced roof. The angles and drop height for this test set were chosen based upon an analysis of a real world rollover, resulting in an initial drop height of 18 inches, 16 degrees of roll angle and 7 degrees of pitch angle. The initial contact point was the top of the driver's side A-pillar. For these tests, a Hybrid III 50th Percentile ATD with a modified lumbar spine (which reduced the seated height by 2 inches) was placed in the right front passenger's seating position and the restraints were normally applied (See Table 1).

The reinforced Escort roof was strengthened by inserting internal steel reinforcements and by filling the steel cavities with structural foam. The additional vehicle weight added by the reinforcements was 26.3 lb (117 N). All of the reinforcements were internal to the existing roof structure and the entire production roof structure was retained. In addition to the reinforced roof structure, this vehicle's upright survival space was increased by approximately 3 inches (80 mm), which was accomplished by lowering the seat base frame. The additional survival space could also be achieved through any combination of lowering the seat, increased roofline and/or improvement the presence of a pretensioner or other device that could draw the occupant into the seat.

Table 1.
1996 Ford Escort Drop Test Conditions

Test Conditions	Production Ford Escort	Reinforced Ford Escort
Drop Height	18.1 in (460 mm)	18.1 in (460 mm)
Impact Speed	6.7 mph (10.8 kph)	6.7 mph (10.8 kph)
Pitch Angle	7 degrees	7 degrees
Roll Angle	16 degrees	16 degrees
Test Weight	585 lb (1,294 kg)	585 lb (1,294 kg)
ATD	Modified Hybrid III	Modified Hybrid III
Restraint Use	Production 3 Point Passive Restraint	Production 3 Point Passive Restraint
Roof Structure	Production	Tubular and Structural Foam Reinforced
Upright head-to-roof Clearance	Production (approximately 3.4 in or 86 mm)	80 mm greater than production (approximately 6.5 in or 165 mm)
Inverted head-to-roof Clearance	Production (approximately 2.2 in or 57 mm)	Modified (approximately 6.0 in or 152 mm)

1998 & 1999 Ford Econoline E-350 15-Passenger Van With Hybrid III Dummy - A pair of Ford E-350 Econoline 15-Passenger Vans, each equipped with a test dummy, were subjected to inverted drop tests. One of the vans was a production vehicle and the other van had a reinforced roof. The vehicles were set up using the same load application angles as those specified in the federal roof strength test, FMVSS 216, namely 25 degrees of roll angle and 5 degrees of pitch angle. The initial contact point was the top of the driver's side A-pillar, which is consistent with real world rollovers. A 12-inch drop height was chosen as appropriate to produce a degree of roof crush consistent with real rollover accidents (See Table 2). For these tests, a Hybrid III 50th Percentile ATD with a modified lumbar spine (which reduced the seated height by 2 inches and weight by

15 pounds) was placed in the driver's seating position and the restraints were normally applied. The test weight for the production vehicle was 6,528 lb (2,960 kg). The test weight for the reinforced vehicle was 6,690 lb (3,034 kg).

Table 2.
1998 & 1999 Ford Econoline Drop Test Setup

Test Conditions	Production Ford Econoline	Reinforced Ford Econoline
Drop Height	12 in (305 mm)	12 in (305 mm)
Impact Speed	5.5 mph (8.8 kph)	5.5 mph (8.8 kph)
Pitch Angle	5 degrees	5 degrees
Roll Angle	25 degrees	25 degrees
Test Weight	6,528 lb (2,960 kg)	6,690 lb (3,034 kg)
ATD	Modified Hybrid III	Modified Hybrid III
Restraint Use	Production 3 Point Passive Restraint	Production 3 Point Passive Restraint
Roof Structure	Production	Tubular and Structural Foam Reinforced
Inverted head-to-roof Clearance	Production (approximately 8.5 in or 216 mm)	Production (approximately 8.5 in or 216 mm)

The reinforced Ford E-350 roof was strengthened by inserting internal steel reinforcements and by filling the steel cavities with structural foam. In the reinforced vehicle, all of the modifications were internal to the existing roof structure and interior. Production restraint systems were used in both vehicles.

<u>1999 Ford F-250 F-series Crew Cab Pickup With Hybrid III Dummy</u> - Dummy-equipped inverted drop tests were conducted on a pair of Ford F-250 Crew Cabs, one production vehicle and the other with a reinforced roof. The test set-up for the pair is presented in Table 3 below. The load application angles used were the same as those specified in FMVSS 216, the federal test for roof strength. In order to evaluate the front roof structure, the top of the driver's side A-pillar was chosen as the initial impact location. The 12-inch drop height was chosen to produce the approximate roof crush of a real world rollover involving a similar vehicle. The Hybrid III 50th Percentile Male was placed in the driver's seat, which was set to its middle position for both tests. The adjustable D-ring was also placed in its middle position for each test. In the production test, the dummy was belted normally using the provided OEM 3-point restraint. In the reinforced test, the dummy was 3-point belted with a pretensioned restraint system, consistent with belt activation prior to the first quarter turn in a rollover [19].

Table 3.
1999 Ford F-series Drop Test Setup

Test Conditions	Production Ford F-series	Reinforced Ford F-series
Drop Height	12 in (305 mm)	12 in (305 mm)
Impact Speed	5.5 mph (8.8 kph)	5.5 mph (8.8 kph)
Pitch Angle	5 degrees	5 degrees
Roll Angle	25 degrees	25 degrees
Test Weight	6,131 lb (2,780 kg)	6,373 lb (2,890 kg)
ATD	Standard Hybrid III	Standard Hybrid III
Restraint Use	Production 3 Point Passive Restraint	Pretensioned 3 Point Passive Restraint
Roof Structure	Production	Tubular and Structural Foam Reinforced
Inverted head-to-roof Clearance	Production (approximately 4.75 in or 121 mm)	Production (approximately 6.75 in or 172 mm)

The reinforced Ford F-250 roof was strengthened by inserting internal steel reinforcements and by filling the steel cavities with structural foam. In the reinforced vehicle, all of the modifications were internal to the existing roof structure and interior. In addition to the strengthened roof structure, the reinforced vehicle test employed a belt pretensioner, which removed 4 inches of the belt with 60-70 lb of resulting belt load prior to inversion.

<u>1986 Ford Econoline E-150 Van With Hybrid III Dummy</u> – In addition to the previous three drop test pairs, a single reinforced drop test was conducted on a 1986 Econoline E-150 Van. A standard Hybrid III test dummy was placed in the front seat compartment and was restrained with the production 3-point belt system. The vehicle was inverted and orientated such that the pitch angle was 5 degrees, the roll angle was 16 degrees, and the initial point of contact was the driver's side A-pillar. The vehicle was then dropped from a height of 24 in (610 mm) (See Table 4).

Table 4.
1986 Ford Econoline Drop Test Setup

Test Conditions	Production Ford Econoline	Reinforced Ford Econoline
Drop Height	N/A	24 in (610 mm)
Impact Speed	N/A	7.7 mph (12.4 kph)
Pitch Angle	N/A	5 degrees
Roll Angle	N/A	16 degrees
Test Weight	N/A	6,373 lb (2,890 kg)
ATD	N/A	Standard Hybrid III
Restraint Use	N/A	Production 3 Point Passive Restraint
Roof Structure	N/A	Tubular and Structural Foam Reinforced
Inverted head-to-roof Clearance	N/A	Production (approximately 6.0 in or 152 mm)

The reinforcements incorporated in the drop test vehicle included a B-pillar area tubular reinforcement and structural foam filling. In this test, the production restraints were applied in a fashion consistent with normal occupant use. The vehicle was then inverted via a vehicle rotational mechanism and the occupant was allowed to move towards the roof to the degree permitted by the restraint system prior to drop.

RESULTS & DISCUSSION

The primary differences between the production and reinforced tests were the amount of roof crush and seat belt loading, which resulted in different dynamic occupant excursion and neck loading. The reduction in neck load in the reinforced vehicle was due to increased dynamic head-to-roof clearance resulting from reduced roof crush and in some cases improved restraint performance (See Figures 1 through 4).

Production 1996 Ford Escort

Reinforced 1996 Ford Escort

Figure 1. 1996 Ford Escort Drop Test Pair Comparison Post Test

Production 1998 Ford Econoline 15 Passenger Van

Reinforced 1999 Ford Econoline 15 Passenger Van

Figure 2. 1998 & 1999 Ford Econoline Drop Test Pair Comparison Post Test

Production 1999 Ford F-250 Crew Cab

Reinforced 1999 Ford F-250 Crew Cab

Figure 3. 1999 Ford F-250 Crew Cab Drop Test Pair Comparison Post Test

Reinforced 1986 Ford Econoline Van

Figure 4. Reinforced 1986 Ford Econoline Van Post Drop

The results from the seven inverted drop tests are summarized in table 5 below.

Table 5.
1999 Ford F-series Drop Test Setup

Vehicle	Static A-Pillar Crush	Neck Load	Belt Load
Production 1996 Ford Escort	5.3 in (134 mm)	2,187 lb (9,727 N)	N/A
Reinforced 1996 Ford Escort	3.5 in (89 mm)	288 lb (1,281 N)	N/A
Production 1998 Ford Econoline	11.2 in (284 mm)	820 lb (3,647 N)	117 lb (520 N)
Reinforced 1999 Ford Econoline	0.6 in (15 mm)	49 lb (218 N)	394 lb (1,753 N)
Production 1999 Ford F-series	8.7 in (221 mm)	1201 lb (5,342 N)	162 lb (721 N)
Reinforced 1999 Ford F-series	0.9 in (23 mm)	-61 lb (271 N)	475 lb (2,113 N)
Reinforced 1986 Ford Econoline	1.5 in (38 mm)	271 lb (1,205 N)	550 lb (2,446 N)

As shown in this summary table, the injurious neck loads experienced by the dummies in the production vehicle are directly correlated to the high levels of vehicle roof crush. Similarly, the dummies in the reinforced vehicle drop tests consistently recorded neck loads well below the artificially low injury value of approximately 450 lb (2,000 N) used in the Malibu Study. The neck loads are significantly lower in the reinforced vehicles because the survival space was maintained during the inverted drop tests. This phenomenon is illustrated in Figure 5 below.

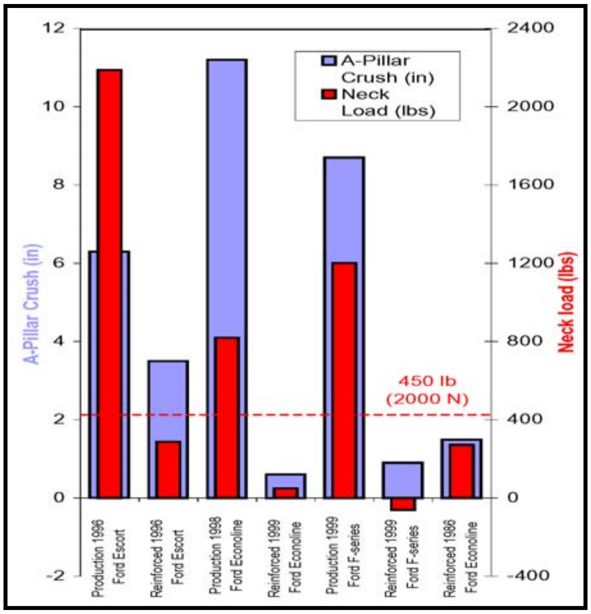

Figure 5. Inverted Drop Test Comparisons With Hybrid III Dummies: A-pillar Crush and Neck Load

The lap belt loads for the inverted drop test matrix were analyzed and compared to the Hybrid III neck loads that were recorded. Lap belt data was not recorded for 1996 Ford Escort drop test pairs, so this drop test was not included in this analysis. As shown in Figure 6 below, neck loads are inversely correlated to the amount of force transferred into the belt system.

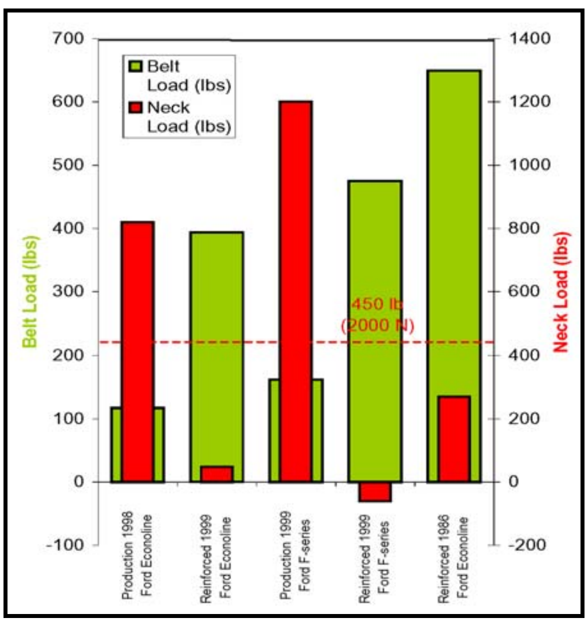

Figure 6. Inverted Drop Test Comparisons With Hybrid III Dummies: Belt Load and Neck Load

In order to further understand the relationship between roof crush, belt loads, and neck injury, the data was normalized and plotted on the same graph for comparison (See Figure 7). This was accomplished by taking the highest value in each of the three categories and setting it to 1.0 and then by expressing the other values as a percentage of that highest value. While this figure does not reflect any numerical data, it allows for a relative comparison between the data.

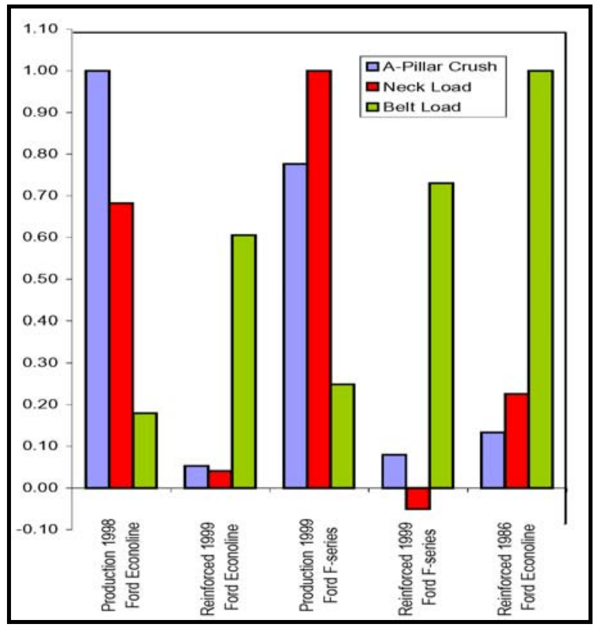

Figure 7. Inverted Drop Test Comparisons With Hybrid III Dummies: Normalized A-pillar Crush, Neck Loads, and Belt Loads

As shown in Figure 7, the production drop test vehicles both experienced high levels of roof crush, high neck loads, and low belt loads. In contrast, all of the reinforced vehicles experienced low levels of roof crush, low neck loads, and high belt loads. The belt loads are high in the reinforced drop tests because the strengthened roofs were able to maintain the occupant survival space and allow the restraints to be loaded dynamically with the occupant weight. Even though the belt loads were much higher in the reinforced drop tests, it does not necessarily reflect the quality of the restraint system. For example, the 1998 & 1999 Ford Econoline drop test pair both utilize the same production restraint system, yet the forces generated in the reinforced drop test are about three times higher than in the production drop test. This is because in the production drop test the survival space was compromised due to roof intrusion before the belt system could effectively restrain the occupant. However, in the reinforced Econoline drop test, the strengthened roof maintained the survival space, allowing the restraints to be loaded dynamically with the occupant weight.

Analysis of the test videos and data have demonstrated that the combination of a small amount of initial inverted head to roof clearance, a high degree of roof crush, and significant occupant excursion results in significant neck loads. In all three of the production drop tests the roof crush clearly preceded the initial compression neck loading, the peak neck loading, and occupant vertical displacement (See Figures 8-10).

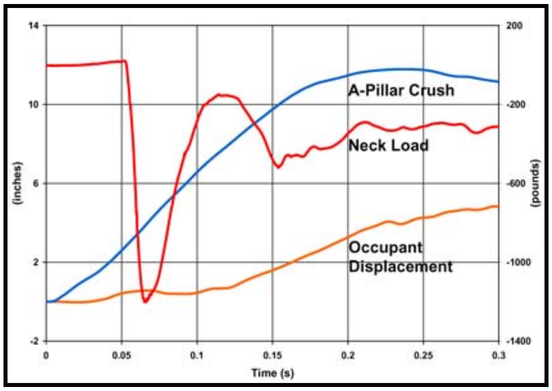

Figure 8. Production 1999 Ford F-250 Time Phasing

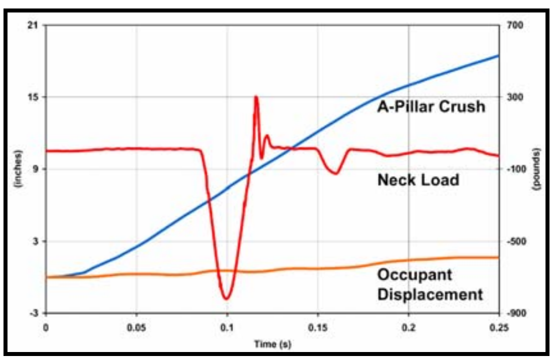

Figure 9. Production 1998 Ford Econoline Time Phasing

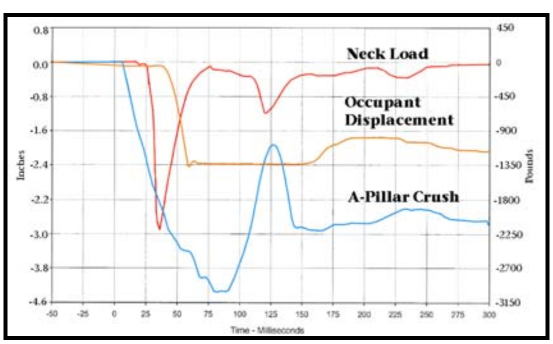

Figure 10. Production 1996 Ford Escort Time Phasing

CONCLUSIONS

- Several inverted drop tests from 12 to 24 in (305 to 610 mm) with corresponding contact speeds of 5.5 to 7.7 mph (8.9 to 12.4 kph) produced significant roof crush in typical production vehicles.
- Roof crush proceeds initial compression neck loading, peak neck loading, and occupant vertical displacement.
- Structural reinforcements to the roof structures resulted in significantly reduced roof crush and low compression and flexion force levels in Hybrid III dummies.
- High Hybrid III neck compression and flexion loads were produced in the production vehicles due to a compromise of occupant survival space and ineffective occupant restraint.
- Significant neck compression and flexion forces only occur when the survival space is compromised by significant roof crush and/or when occupant excursion reduces the effective head-to-roof clearance.
- The degree of neck axial compression and flexion loads in the Hybrid III dummy and therefore, potential for injury, is a function of the initial head-to-roof clearance, the restraint effectiveness and the extent of roof crush.
- Strong roofs along with adequate initial headroom can maintain occupant survival space and will result in increased belt loads and reduced neck loads well below injury thresholds.

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