Do Non-Complying Bull-Bars Increase the Injury Risk to Occupants of Other Vehicles?

SURATNO Basuki[1], BLACK David[2], DAL NEVO Ross[2], PAINE Michael[3] and SIMMONS Keith[1]

[1]NSW Centre for Road Safety, Transport for NSW, 18 Lee Street, Chippendale, NSW 2008
[2]Crashlab, Roads and Maritime Services, 409 Great Western Highway, Huntingwood, NSW 2148
[3]Vehicle Design and Research, 10 Lanai Place, Beacon Hill, NSW 2100

Basuki.Suratno@transport.nsw.gov.au

1. Introduction

Vehicle frontal protection systems for motor vehicles (referred to as bull-bars) are commonly fitted to four-wheel-drive vehicles (4WDs) or sport utility vehicles in Australia. They are purportedly fitted to reduce damage to the front of the vehicle in the event of an animal strike.

Previous research on the impact characteristics of current bull bar designs show that many bull-bars pose an increased risk to pedestrians and other vulnerable road users in the event of a crash, Anderson et al (2006). Furthermore, those authors report metal bull bars, and steel bull bars in particular, are likely to cause serious injury in crashes with pedestrians, and that most of the bull-bars tested were more dangerous than the front of the vehicle to which they were attached.

Research suggests bull-bars also pose an extra hazard to other vehicle occupants in the event of side impact crashes, increasing the risk of head injury due to the increased height of impact and intrusion of the bull bar into the cabin of the impacted vehicle (Rechnitzer, 1993).

Research studies have shown that side impact crashes account for a substantial proportion of injuries and fatalities to passenger car occupants. This is mainly due to the minimal distance between impact point and occupant. Modern side impact protection systems include thorax-protecting side airbags, usually built into the side of the seat, and head-protecting side airbags such as inflatable side curtains. These are also known as head-protecting technologies (HPT).

Earlier studies on the effects of bull-bars in vehicle crashes were conducted before HPT became common on Australian vehicles and do not take into account the potential for some types of bull-bars to prevent correct HPT deployment.

There are a wide range of bull-bar designs and consequently a wide range of extra risk to other road users. Some bull-bar designs that are high-mounted and result in a point of first contact that matches the height of the side windows of passenger cars are of particular concern.

In NSW, bull-bars fitted to vehicles under 3.5 ton GVM that were manufactured after 1 January 2003 must comply with Australian Standard 4876.1-2002 (AS 4876.1-2002) *Motor vehicle frontal protection systems-Road user protection* with exception of Clause 3.2 which is the road user protection criterion requirement. Currently, NSW is the only Australian jurisdiction that requires bull-bars to comply with this standard.

AS 4876.1-2002 requires that bull-bars have “a profile that generally conform to the shape, in plan view, front view and side view, of the front of the vehicle to which it is fitted”. Examples of “geometrically” complying and non-complying bull-bars are shown in Figure 1 and Figure 2 respectively.

The focal question is, What injury risks are associated with a bull bar that complies with the Australian Standard compared to a non-complying bull-bar when fitted to 4WDs at standard and raised ride heights for the near side occupant of a struck vehicle in side impact crashes?

Figure 1. 4WD vehicle fitted with geometrically complying bull-bar

Figure 2. 4WD vehicle fitted with geometrically non-complying bull-bar

It is hypothesised that geometrically non-complying bull-bars fitted to 4WD vehicles increase the risk of injury to occupants of passenger vehicles side impacted by the said vehicle, particularly given the anecdotal finding that these bull-bars are often fitted to raised height 4WD vehicles. The objectives of this study were therefore to:

(i) compare the injury risk to the near-side occupant of a passenger vehicle side-impacted by a 4WD without a bull-bar fitted to the injury risk from the ANCAP mobile deformable barrier (trolley) test,

(ii) compare the injury risk to the near-side occupant of a passenger vehicle side-impacted by standard height and raised height 4WD vehicles fitted with a geometrically complying bull-bar, and

(iii) compare the injury risk to the near-side occupant of a passenger vehicle side-impacted by a 4WD vehicle fitted with geometrically complying and non-complying bull-bars at raised ride height.

2. Methodology

To meet the objectives of this study, a series of side-impact tests were conducted using a relatively new popular large passenger car as the target vehicle and two popular models of 4WD utilities as the bullet vehicles.

2009 Toyota Camry was chosen by the authors as it represents a popular large passenger vehicle. This model vehicle was fitted with head-protecting and thorax-protecting side airbags. A 2005 Holden Rodeo and a 1992 Toyota Hilux Utility were chosen as the bullet vehicles. These vehicles were chosen as they are representative of the most common 4WD fitted with a bull-bar.

Two different types of full width steel bull-bars were examined, designated as a geometrically "complying" bull-bar in which the direction of the top part was rearward facing and a geometrically "non-complying" bull-bar where the top of the bar protrudes forward (see Figure 2). These designs represent the common types of bull-bars fitted to 4WD vehicles in Australia.

Two 4WD vehicles with different suspension height were examined, designated as "standard" and "raised" height. The effect of vehicle height was investigated using two bullet vehicles of different height. The Holden Rodeo retained its original manufactured height with a cross-bar/front-chassis mid height of 510 mm and the Toyota HiLux was raised by 65mm to give a front-chassis mid height of 600 mm. A test matrix detailing the vehicle configurations is shown in Table 1.

In order to separate the two parameters investigated in this study i.e. effects of bull-bar design and vehicle height, two tests were conducted for each parameter. As seen in Table 1, tests 4 and 5 were conducted at the same vehicle height with different bull-bars to isolate the effect of bull bar design. Similarly, tests 3 and 4 were done using the same bull-bar type (geometrically complying) at two different heights to isolate the effect of vehicle height when fitted with a bull bar.

All tests were conducted at the Crashlab Crash Barrier facility to ANCAP side impact test requirements and *Australian Design Rule 72/00 Dynamic Side Impact Occupant Protection* (ADR 72); however, the velocity of the bullet vehicles were adjusted to match the impact energy of ANCAP side impact test. For example, the weight of the Holden Rodeo was 1690 kg, so to achieve the same impact energy as the 950 kg mobile deformable barrier impacting at a speed of 50 km/hr, the speed of the Rodeo was adjusted to 37.5 km/hr. Similarly, the impact speed for Toyota Hilux was adjusted to 38.9 km/hr based on its weight.

Table 1. Test Matrix

Test No	Test Description	Bullet Vehicle	Bullet Vehicle's test specifications			Bull-bar
			Weight (kg)	Speed (kph)	Front mid chassis height (mm)	
1	ANCAP Side Impact	Trolley	950	50	425	No bull-bar
2	Baseline	Rodeo	1690	37.5	510	No bull-bar
3	Std Height Compliant	Rodeo	1690	37.5	510	Complying
4	Raised & Compliant	Hilux	1565	38.9	600	Complying
5	Raised & Non-compliant	Hilux	1565	38.9	600	Non-complying

The test configurations for Tests 2 to 5 are presented in Figure 3 to Figure 6.

A side impact dummy (EuroSid2) representing a 50^{th} percentile adult male was positioned in the front seat on the impact side of the target vehicle. The dummy was prepared, positioned and instrumented as per ANCAP procedures to measure the following performance criteria: Head Injury Criterion (HIC), rib deflection criterion, viscous criterion, Pubic Symphysis Peak Force (PSPF) and Abdominal Peak Force (APF).

EuroNCAP side impact assessment limits values (EuroNCAP, 2004) and ADR 72 performance criteria along with injury risk curves developed by Kuppa (2004) were used to assess the injury risk to the near-side occupant of the target vehicle.

The results obtained from ANCAP side impact test for 2011 Toyota Camry were used to provide a comparison in term of the injury risk to occupant of the target vehicle. While the test vehicles used was the earlier 2009 Camry, it was also fitted with head-protecting and thorax-protecting side airbags and the authors of this paper were of the view that the load bearing structure was similar to the current model.

The 2011 Camry scores an ANCAP total rating of four stars and scores 16 out of 16 in the side impact crash test with detail scorings in side impact 4 out of 4 points in all body regions. This illustrates a high level of protection of the head, chest, abdomen and pelvis, suggesting a very low risk of serious injury or death resulting from impact to these areas.

Figure 3. Test 2 Configuration

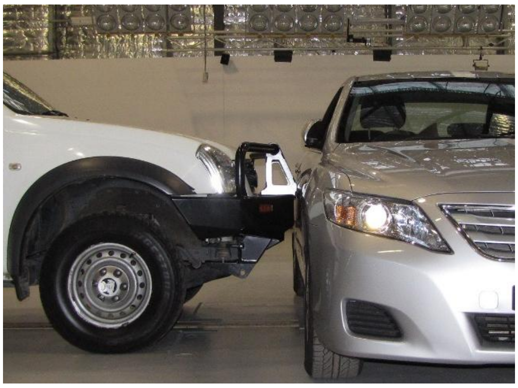

Figure 4. Test 3 Configuration

Figure 5. Test 4 Configuration

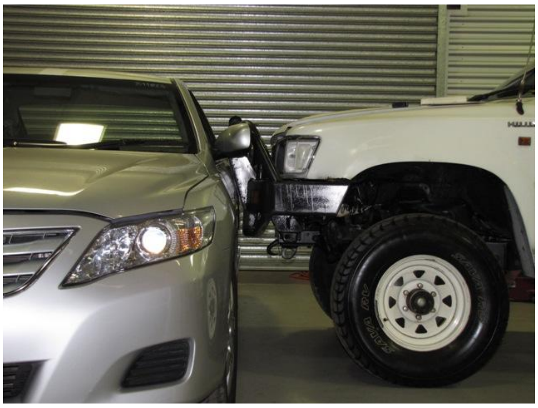

Figure 6. Test 5 Configuration

3. Results and Discussion

Table 2 summarises responses measured from side impact dummy from all four tests and ANCAP side impact test.

Table 2. Dummy measurements

Test No	Test Description	HIC	Rib Compress (mm)			Rib Viscous Criterion (m/s)			APF (N)	PSPF (N)
			Up	Mid	Low	Up	Mid	Low		
1	ANCAP Side Impact	28	14.30			0.04			640	1750
2	Baseline	29	13.1	11.9	14.8	0.04	0.06	0.08	660	2530
3	Std Height Compliant	55	20.3	19.2	22.9	0.11	0.11	0.20	900	2400
4	Raised & Compliant	104	36.8	34.2	33.3	0.43	0.42	0.34	750	1270
5	Raised & Non-compliant	122	23.6	33.8	48.0	0.22	0.50	1.08	1020	1860

APF = Abdominal Peak Force *PSPF = Pubic Symphysis Peak Force*

As seen on the above Table, the results from dummy measurements indicated that in all tests, except test 5, all performance criteria set out in ADR 72 were met and within EuroNCAP upper limits. In test 5 where the bullet vehicle was raised and fitted with a non-complying (forward facing) bull-bar, the dummy's rib compression and viscous criterion were outside both ANCAP and ADR 72 requirements (highlighted in yellow). This could lead to higher risk of chest injuries to the occupant of the struck vehicle.

Detailed observations on rib compression and viscous criterion indicated that both measurements increased toward the lower part the occupant's thorax. This could be attributed to rotation of the bar during the impact as seen in Figure 7

Figure 7. Series of front view of test 5 showing bull-bar rotated backward

3.1. Injury Risk Assessment

Injury criteria and their associated injury risks developed by Kuppa (2004) were used to analyse risk of injuries to head, chest, abdomen and pelvis using the responses obtained from the EuroSID2 dummy.

Risk of Head Injuries

Head injury risks in crash test dummies are normally assessed using the linear centre of gravity head acceleration or the Head Injury Criterion (HIC) that is derived from the head acceleration. Head injury risk curve as proposed by Kuppa (2004) was used to estimate AIS 2+ head injuries probability. The results are presented in Table 3

Table 3. Risk of Head Injuries

Test	Test Description	HIC36	AIS 2+
1	ANCAP Side Impact	28	0%
2	Baseline	29	0%
3	Std Height Compliant	55	0%
4	Raised & Compliant	104	0%
5	Raised & Non-compliant	122	1%

In all tests, the vehicle head-protection side airbags were deployed on time (approximately 7.7 ms after first contact in the impact) protecting the dummy head from striking either the vehicle structure or the intruding the bull-bar. This resulted in HIC under the minimum EuroNCAP limit of 600 which corresponds to 5% AIS 3+ injury risks. Although the HIC in the non-complying bull-bar test (Test 5) was at least more that four fold that of the ANCAP test, the absolute risk of head injury was still low.

Risk of Chest Injuries

Chest injury risks were estimated using rib compression criteria. The AIS3+ and AIS4+ chest injury risk curves developed by Kuppa (2004) were used to estimate chest injury probability using the dummy rib compression data. The results of both AIS3+ and AIS4+ chest injury risks are presented in Table 4.

AIS3+ chest injury risk equates to 2 to 3 rib fractures with possibly hemothorax or pneumothorax injury. An AIS4+ chest injury risk suggests more than 4 rib fractures with hemothorax or pneumothorax injury and flail chest injury (Pike, 1990).

Table 4. Rib Compression

Test	Test Description	Max Rib Def (mm)	AIS 3+	AIS 4+
1	ANCAP	14.3	20%	6%
2	Baseline	14.8	20%	6%
3	Std height compliant	22.9	27%	9%
4	Raised & compliant	36.8	42%	16%
5	Raised & non-compliant	48.0	55%	25%

Results from Test 1 and 2 indicate that the near-side occupant of the target vehicle would receive the same chest injury risk when side-impacted by either a mobile deformable barrier used in ANCAP or a standard height 4WD with no bull-bar. However, there was a slight increase (of 7%) in chest injury risk to the struck vehicle occupant when side-impacted by a standard height 4WD fitted with complying bull-bar (Test 3).

A raised height 4WD vehicle fitted with compliant bull bar (Test 4) increased the risk of AIS3+ and AIS4+ chest injury risk from 27% to 42% and from 9% to 16% respectively when compared to standard height compliant bull bar 4WD vehicle (Test 3). This is almost a doubling of the injury risk.

The near-side occupant of the struck vehicle had a further increased risk of AIS3+ and AIS4+ chest injuries from 42% to 55% and from 16% to 25% respectively when side-impacted by a raised height 4WD fitted with non-complying bull-bar (Test 5) compared to the raised height 4WD fitted with a complying bull-bar (Test 4). When compared to the complying bull-bar at standard ride height (Test 3), the raised height non-complying bull bar increased the risk of AIS3+ and AIS4+ chest injuries from 27% to 55% and from 9% to 25% respectively. This represents more than double the risk of an AIS3+ injury and almost triple the AIS4+ injury risk.

Risk of Abdominal Injuries

Risk of abdominal injuries to occupant of the target vehicles was estimated using Abdominal Peak Force (APF) measured from the dummy. Similarly, AIS3+ abdominal injury risk curve developed by Kuppa (2004) was used and the results from all five tests were tabulated in Table 5. As seen, although APF was almost double in Test 5 compared to ANCAP test, the absolute risk of abdominal injury was still low.

Table 5. Abdominal Responses

Test	Test Description	APF (N)	AIS 3+
1	ANCAP	660	1%
2	Baseline	660	1%
3	Std height compliant	900	2%
4	Raised & compliant	750	1%
5	Raised & non-compliant	1020	2%

Risk of Pelvic Injuries

Similar to the above analyses, risk of pelvic injuries was estimated using Pubic Symphysis Peak Forces obtained from the dummy. AIS2+ and AIS3+ pelvic injury risk curves developed by Kuppa (2004) were used and the results are presented in **Table 6**.

As shown, the pelvic injury risks in all tests are very low. This could be attributed to the presence of thorax-protection side airbag in this vehicle model and were deployed during the impact. The earlier version of Camry without thorax-protection side airbag showed that the dummy's PSPF was 3050N which would be equal to 19% AIS+2 pelvic injury risk.

Table 6. Pelvic Dummy Responses

Test	Test Description	PSPF (N)	AIS 2+	AIS 3+
1	ANCAP	1750	3%	0%
2	Baseline	2530	9%	1%
3	Std height compliant	2400	8%	1%
4	Raised & compliant	1270	1%	0%
5	Raised & non-compliant	1860	3%	0%

3.2. Key findings

Key findings of this study are:

- The 4WD vehicle with no bull-bar impacting at 37.5 km/hr did not appreciably increase the risk of injury to the near-side occupant of the struck vehicle when compared to the ANCAP 50 km/hr side impact test.
- The 4WD vehicle with complying bull-bar increased the risk of AIS3+ chest injury to the near-side occupant of the struck vehicle by approximately 7%.
- The raised 4WD vehicle fitted with the complying bull-bar further increased the risk of AIS3+ chest injury to the near-side occupant of the struck vehicle from 20% to 42%, more than double the injury risk.
- The raised 4WD vehicle fitted with the non-complying bull-bar increased the risk of AIS3+ chest injury to the near-side occupant of the struck vehicle by a further 13% when compared to the complying bull-bar at the same raised height; or approximately double the injury risk of a standard height 4WD fitted with a complying bull-bar. The risk of an AIS4+ injury from this configuration vehicle was almost triple than that of the standard height vehicle fitted with a complying bull-bar.

4. Limitation

The results presented in this paper are made from observations of two models of 4WD utility vehicles as the bullet vehicle and one model of target vehicle. Other target vehicles side-impacted with other bullet vehicle may behave differently.

Impact speeds used in the tests were more than 10km/h below the ANCAP/ADR 72 impact speed of 50km/h used as a comparison. This was intended to achieve the same impact energy as the ANCAP test which is a reasonable objective for injury risk resulting from intrusion into the passenger compartment. However the lower speed was likely to have been less challenging for the airbag deployment systems. At higher speeds it is possible that the side airbags and/or curtains might not deployed correctly and so expose the occupants to greater risk of injury.

5. Conclusions

Based on the dummy responses, the results from this study suggest that complying bull bars fitted to standard height vehicles only produce a small increase in injury risk. Raising the height of the vehicle and/or fitting non-complying bull bars can both individually increase the risk of injury by double that of just a compliant bull-bar.

Evidence suggests raising the ride height of a 4WD not fitted with a bull-bar will increase the injury risk for occupants of the struck vehicle, however further tests are required to confirm this.

At the current test speed, both complying and non-complying bull-bars did not prevent the correct deployment of the HPT, but further tests will be conducted to investigate their effect at normal ANCAP/ADR 72 test speed.

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