ROADSIDE HAZARD AND BARRIER CRASHWORTHINESS ISSUES CONFRONTING VEHICLE AND BARRIER MANUFACTURES AND GOVERNMENT REGULATORS.

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ABSTRACT

Run-off-road crashes into roadside hazards that include impacting rigid objects and roll-over constitute approximately 40% of road fatalities and cross over two car frontal collisions account for around 7% of fatalities in Australia. Considerable onus to protect vehicle occupants during such crashes sits with vehicle manufactures. It is clear from research to date, however, that side impacts into narrow objects beyond impact speeds of 40 km/hr, head-on and large engagement offset crashes at closing speeds of 120 km/hr, and roll-over crashes are presently at the limits of survivability.

One way of protecting occupants in such crashes is to use a roadside or median barrier to safely redirect the vehicle. Road crash barriers can in themselves be hazardous unless designed properly. Errant vehicle redirection should occur so that air bag and seat belt pretensioning systems do not fire and rollover does not occur. Research into roadside barrier crash tests carried out by the Department of Civil Engineering at Monash University over the past decade, has revealed some key crashworthiness characteristics that both vehicle and barrier manufacturers alike need to consider. This paper presents results of crash tests that provide some insight into vehicle-barrier crash pulses, occupant and vehicle kinematics and desirable occupant protection systems related to existing barrier profiles and properties and what are the most suitable vehicle and barrier crashworthiness features essential for safe vehicle redirection. The paper also argues, using some real-world examples, in favour of bringing together road designers and car manufacturers with associated regulatory bodies to emphasise a holistic perspective to enhance occupant protection in road crashes.

INTRODUCTION

One way of safely redirecting an errant vehicle away from a hazard, such as a roadside tree or oncoming traffic, is to use a roadside or median barrier. The most commonly used barriers are made from either concrete and/or steel. In the case of concrete barriers they are usually fixed such that when struck, deformation is small. Hence they are commonly referred to as rigid concrete barriers. Steel tubing can be fixed to the top of concrete barriers to provide extra height in order to prevent vehicles with a high centre of gravity (COG), e.g. trucks, from rolling over the top of them.

Steel barriers can be constructive from guardrail, wire rope and tubular sections. Steel barriers are often used to reduce the severity of the crash because they deform when struck, hence they are often referred to as semi-rigid or flexible barriers systems.

Another form of barrier that is commonly used on roads is the temporary barrier for road works. These can be made again either from concrete or steel and, more recently, are being constructed from plastic.

Ideally, roadside safety barriers when struck by an errant vehicle, should redirect the vehicle away from the hazard within a narrow angle so that it follows the line of the barrier while at the same time does not gyrate, overturn or result in any significant damage to the impacting vehicle, or subject the occupants to life-threatening decelerations. The best way of achieving this is to redirect and/or decelerate the vehicle over a short distance that is well within human tolerance/comfort levels.

When a barrier moves sideways during impact this helps reduce the severity of the crash. This movement sideways is known as the barrier's "working width". The working width for a rigid barrier system is in the range from zero to only a few centimetres. On the other hand, the working width of flexible systems can be as much as three to four metres in the extreme but preferably should be no more than one to two metres.

The main issue for car manufacturers is to understand how flexible systems can affect timing of the air bag triggering. Of particular concern is the issue of an airbag firing late in the impact event when the occupant's head has already moved close to the airbag cover.

The main issue for barrier designers, barrier manufacturers and road authorities is to ensure that when a vehicle strikes the barrier system the airbags do not unnecessarily fire and/or result in a vehicle rollover. Firing of an airbag considerably hinders the driver's recovery process. Similarly rollovers need to be avoided because regulations at this present time do not adequately cover rollover crashes and hence rollover roof strength and seat belt and curtain triggering to prevent ejection.

In regards to temporary barriers, the main issue barrier designers need to be aware of is that the working width of the barrier does not encroach into the work zone where workers or pedestrians could possibly be struck.

To assess the crashworthiness characteristics of barrier systems it is useful to recall how the systems were developed over the past 60 years.

Concrete barriers

Concrete safety barriers are widely used where there is no room to accommodate a working width for a deforming barrier, such as narrow medians, bridge barriers and roadsides where hazardous objects are close to road edges. The other reason such barriers are used is that repair maintenance costs are low when these barriers are struck.

Currently, there are four major types of concrete barriers: the New Jersey concrete barrier, the F-shape concrete barrier, the Single-slope concrete barrier and the Vertical concrete barrier. These concrete barriers are someties referred to as "Safety Shape Barriers" (Sicking, 2004). They have all been crash tested and can be used as roadside barriers, median barriers and bridge barriers. Generally, these concrete barriers when adequately designed and reinforced may all be deemed to meet Test Level 4 of NCHRP Report 350 (Ross, Zimmer and Michie, 1993) at the standard height of 810 mm and meet Test Level 5 when the design height is 1070 mm (AASHTO, 2002). Figure 1 shows the cross section profiles of the New Jersey, the F-shape and the Single-slope median concrete barrier.

The New Jersey barrier is the most widely installed concrete barrier. The F-shape barrier, which is supposedly named on the basis that this geometry was the sixth alternative identified and was labelled with the sixth letter of the alphabet: F, performs better for small vehicles with respect to vehicle roll than the New Jersey barrier, but has not been as widely used. The Single-slope barrier, also called Constant-slope barrier, is the most recent generation in the evolution of concrete barrier systems and is becoming popular because the pavement adjacent to it can be overlaid several times without changing the performance of the barrier (Ray and McGinnis, 1997).

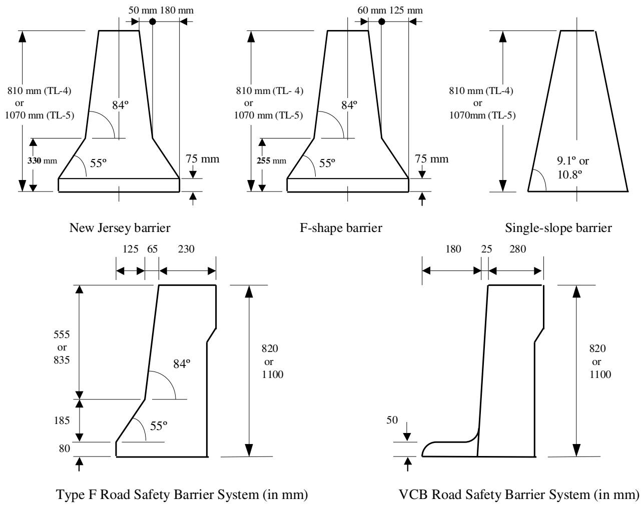

Figure 1 Profiles of more common concrete barriers used in the USA and Australia

In Australia, two types of rigid road safety barrier systems are recommended in AS/NZS 3845: the Concrete Road Safety Barrier Type F and the Vertical Concrete Road Safety Barrier (VCB) (AS/NZS, 1999; 1999). Figure 1 shows the Australian standard Type F and the VCB roadside safety barrier system, which are essentially the same as the USA standard F-shape and the Constant slope concrete barrier respectively.

Concrete barriers were first used in the 1940s in California, USA. The aim was to minimise the number of errant trucks penetrating the barrier and eliminate the need for costly and dangerous barrier maintenance in narrow medians. The widely used New Jersey concrete barrier was tested at the GM proving grounds with the intention of developing a barrier that minimised vehicle damage when struck at a shallow angle. This barrier was first installed in New Jersey in 1955 and was upgraded to the currently used profile in 1959. Apparently no crash tests were carried out in the development of the upgraded New Jersey barrier. Modifications were based on real world accident experience only (Ray and McGinnis, 1997).

As the traffic volume and speed from the early 1950s began to change, concrete bridge barriers were being used to prevent vehicles from penetrating through bridge rails. As a result, the state of California (Beaton, 1956) performed a series of five full-scale crash tests to optimise concrete bridge barrier designs in 1955. Since then, many full-scale crash tests have been carried out in order to develop concrete road or bridge barriers that can prevent penetration of the barrier and redirect a vehicle with as little occupant risk and vehicle damage as possible. As a result, some concrete barriers were proved to have satisfied impact performance such as the F-shape barrier (developed in 1976) and the Single-slope barrier (developed in 1989), whereas some other concrete barriers were demonstrated to have unacceptable impact performance such as the GM-shape concrete barrier (Michie, 1971; Ray and McGinnis, 1997).

In Europe, several types of concrete barriers were developed in the 1960s, such as the German DAV concrete median barrier, the Belgian Trief concrete guardrail, the French Sabla concrete guardrail, the Italian Sergad concrete guardrail and the Italian Vianini concrete median barrier (Michie, 1971). However, most of these concrete barriers were proven to be unsatisfactory after tests were carried out and from real world crash experience. European countries also currently use New Jersey shape for their standard concrete barriers (FEMA, 2000).

Table 1 summarises most of the full-scale crash tests carried out so far on concrete road safety barriers. Basically, these crash tests were carried out to assess the impact performance of a variety of concrete barrier designs. The impact load generated by a car crashing into a concrete barrier can be determined if the barrier is instrumented with load cells. However, such research tests are scarce. Only two research papers written by Neol, Hirsch, Buth and Arnold (1981) and Hellmich (2002) were found in literature by the authors, where full-scale crash tests were specifically performed to investigate the possible impact loads of concrete bridge barriers.

Neol et al. (1981) conducted a series of eight crash tests where two subcompact 817 kg (1800 lb) sedans, two compact 1022 kg (2250 lb) sedans, two full-sized 2043 kg (4500 lb) sedans, one 66-seat 9082 kg (20000 lb) city bus and one two-axle 14531 kg (32000 lb) inter-city bus were used to crash into a vertical concrete wall at a nominal speed of 96.6 km/h (60 mph). The impact angle was between 15 degrees and 24 degrees. The concrete wall was specifically instrumented to measure the magnitude and location of vehicle impact forces. To handle the force spikes observed from the instrumented concrete wall outputs, Neol et al. made some judgements and decided to determine the maximum impact force by using the largest 50 ms average force. The results are summarised in the first eight tests in Table 1. Hellmich (2002) also used a 13 ton bus crash test into an instrumented “Salzburger Klaue” concrete bridge barrier, which is quite similar to the New Jersey barrier, to investigate the impact load level. The peak impact load was recorded as 510 kN for this 70 km/h and 20° test.

The impact load of a vehicle crashing into a concrete barrier can also be determined if the deceleration data at the centre of gravity of the car is recorded during the impact. Nevertheless, as can be seen in Table 1, only several classes of vehicles were selected and tested at a limited number of impact speeds and angles. There is still a need to understand how the impact loads, and hence deceleration forces, are generated and how to calculate them, when different vehicles crash into a concrete barrier at different speeds and angles.

Steel Guardrail barriers

One of the other most commonly used barriers are constructed from steel guardrail or W-beam. Post-and-beam barrier systems can be generally categorised into weak-post-and-beam barrier systems and strong-post-and-beam barrier systems. Weak-post-and-beam barrier systems can be further grouped into weak-post cable barriers, weak-post W-beam barriers and weak-post box beam barriers, whereas strong-post-and-beam barriers can be further divided into strong-post W-beam barriers and strong-post Thrie-beam barriers (Ray and McGinnis, 1997).

Among these post-and-beam barrier systems, the strong-post W-beam barrier is the most common in use today. A typical strong-post W-beam barrier system consists of steel or wood posts that support a W-beam steel rail that is blocked out from the posts with routed timber, steel or recycled plastic spacer blocks (AASHTO, 2002). A variety of posts and blocks for strong-post W-beam barriers are being used in different countries.

In the USA, a wide variety of cross-sections and materials for posts and blocks have been evaluated via numerous full-scale crash tests, such as W150×13.5 steel, W150×16.6 steel, 110×150 mm cold formed channel steel (Charley Post), 150×200 mm rectangular wood, 200×200 mm square wood, 150 mm diameter round wood and 150×200 mm reinforced concrete (Ray and McGinnis, 1997; Plaxico, Ray and Hiranmayee, 2000). The W150×13.5 steel and 150×200 mm rectangular wood posts and blocks are the most common types used, while some of the posts like channel section steel posts and concrete posts have virtually not been used anymore. Figure 1 shows the typical types of strong-post W-beam barrier widely used in the USA (WPI, 2004).

The typical post length is 1830 mm and the post spacing is 1905 mm. Strong-post W-beam barriers using wood or steel posts and wood blocks, as shown in Figure 2, have passed NCHRP Report 350 Test Level 3 crash tests, whereas strong-post W-beam barriers using steel posts and steel blocks (bottom image in Figure 2) have only passed NCHRP Report 350 Test Level 2 crash tests (Ray and McGinnis, 1997; AASHTO, 2002).

Table 1 Summary of full-scale crash tests on concrete safety barriers

Barrier type	Barrier height (mm)	Vehicle mass (kg)	Impact speed (km/h)	Impact angle (degrees)	Maximum impact load or deceleration a_x (g's)	a_y (g's)	Performance comment	Test institute and Year	Ref.
Vertical Concrete Barrier	1070	931	95	15.5	81.9 kN			Texas Transportation Institute (TTI) 1980~ 1981	Neol *et al.* (1981)
		949	94	21.0	93.9 kN				
		1271	94	15.0	82.3 kN				
		1285	90	18.5	97.9 kN				
		2125	85	15.0	194.0 kN		Redirected		
		2152	96	24.0	309.7 kN		Redirected		
		9094 School bus	93	15.0	328.4 kN		Redirected		
		14537 Inter city bus	97	15.0	939.0 kN		Redirected		
Vertical Concrete Parapet	810	892	97.3	21	8.0	14.0	Redirected	TTI 1987~ 1988	Buth *et al.* (1990)
	810	2615 (Pickup)	96.1	20.2	5.7	13.1	Redirected		
	810	8172 Single-unit truck	80.5	14	1.7	4.6	Redirected, rolled 90º		
	1070	22723 Tractor trailer	82.7	16.2	3.3	3.7	Redirected, rolled 90º		Menges *et al.* (1995)
Texas Concrete Median Barrier	810	1910	98	7	8.4	29.2		TTI 1973	Troutbeck (1975)
	810	1910	98	15	7.8	14.0			
	810	1920	90	25	10.3	13.3			
	810	1800	100	25	8.7	16.1			
	810	21770 Tractor trailer van	55	16			<8º Roll		
	810	21770	56	19			<8º Roll		
	810	21770	72	15			<17º Roll		
Concrete Median Barrier	810	9203 School bus	99	15			Rolled over	Dynamic Science Inc. (DSI) 1981	Hirsch (1986)
	810	9075 School bus	97	16			Rolled over		
	810	9080 School bus	93	15			Rolled over	TTI 1984	
	810	18169 Scenic cruiser bus	89	16.2			Redirected	DSI 1981	
	810	18174 Scenic cruiser bus	87	14			Redirected		
Concrete Median Barrier	810	8281 (Truck)	97	15			Rolled over	TTI 1985	Hirsch (1986)
	810	8251 Tractor trailer van	85	15			Mounted	DSI 1981	
	1070	36402 Tractor trailer van	84	15			Rolled over	TTI 1985	
	1070	36688 Tractor trailer van	84	16.5			Redirected	TTI 1984~ 1985	
Concrete parapet	2290	36374 Tractor trailer tank	83	15			Redirected		
Single-Slope Barrier	1070	817	97.7	19.9	6.5	15.3	Redirected	TTI 1989	Beason (1989)
	1070	2043	101.5	26.5	6.4	13.1	Redirected	TTI 1989	

Table 1 (Con't) Summary of full-scale crash tests on concrete safety barriers

Barrier type	Barrier height (mm)	Vehicle mass (kg)	Impact speed (km/h)	Impact angle (degrees)	Maximum impact load or deceleration		Performance comment	Test institute and Year	Ref.
					a_x (g's)	a_y (g's)			
New Jersey Barrier	810	2060	61	7				California Division of Highway 1968~1971	Troutbeck (1975)
	810	2060	105	7					
	810	2060	101	25					
	810	2260	72	7					
	810	2260	103	7		4.8			
	810	2260	106	7		4.8			
	810	1800	82	25					
New Jersey Barrier	810	2052	94.3	16.2			Redirected	TTI 1986	Ray and McGinnis (1997)
	810	1021	94.8	15.5			Redirected	Southwest Research Institute (SwRI) 1976	
	1070	809	96.4	14			Redirected	TTI 1986	
	1070	36402(36000V)	83.8	16.5			Redirected	TTI 1986	
	1070	2000 (Pickup)	101.2	25.6			Redirected	TTI 1995	
	810	1244	81	45			Rolled over, airborne	Monash University 2000	Grzebieta *et al*, (2002)
	810	1244	112	20			Redirected, airborne		
	810	1244	110	20			Redirected, airborne		
New Jersey Bridge Rail	750	13000 (Bus)	70	20	510 kN		Redirected	Ministry of Traffic, Austria 2002	Hellmich (2002)
	810	2599 (Pickup)	92.8	20.6	6.6	7.3	Redirected	TTI 1988	Buth *et al.* (1990).
	810	8172 Single-unit truck	83.0	15.5	3.2	2.5	Redirected		
Ontario Tall Wall	1070	36287 (Tractor trailer)	79.8	15.1			Redirected	TTI 1990	Ray and McGinn (1997)
F-shape Barrier	810	1982	98.8	15.2			Redirected	SwRI 1976	Ray and McGinn (1997)
	810	1021	90.8	14.3			Redirected		
F-shape Bridge Railing	810	893	96.7	21.4	8.0	12.8	Redirected	TTI 1987 ~ 1988	Buth *et al.* (1990).
	810	2624 (Pickup)	105.2	20.4	4.7	13.1	Redirected		
	810	8172 Single-unit truck	83.8	14.8	1.4	3.9	Redirected		
	1070	18414 Scenic cruiser bus	89.6	15.7	1.5	6.5	Redirected		Menges *et al.* (1995)
	1070	22700 (Tractor trailer)	84	14	2.2	4.7	Redirected		
Single-Slope Bridge Rail	810	2076 (2000P)	97.2	25.5	7.3	13.3	Redirected with airborne	TTI 1994	Mak *et al.* (1995)
	810	8172 (8000S)	82.1	10	1.3	2.7	Redirected, rolled 90º	TTI 1994	
	810	8172 (8000S)	82.5	17.9	2.0	5.6	Redirected, rolled 90º	TTI 1994	

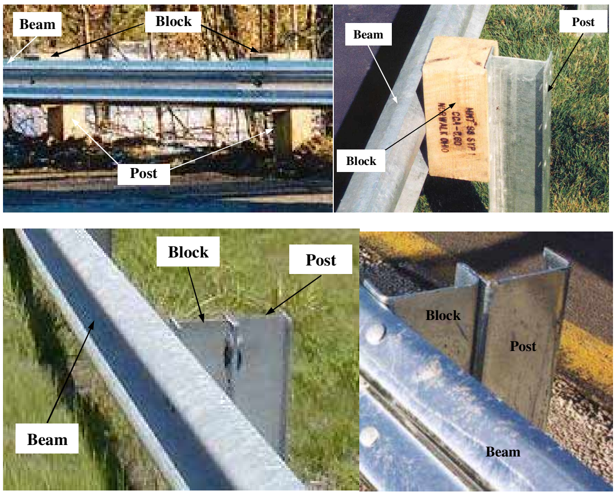

Figure 2 Guardrail barriers used in the US and in Australia

In the Australian standard AS/NZS 3845:1999, only the 110×150 mm channel steel post and block, as shown in Figure 3, are recommended for strong-post W-beam barriers. The standard post spacing is 2000 mm. The post length is 1800 mm. It is stated in the standard that such W-beam barrier systems comply with the requirements of Test Level 3 (Standards Australia, 1999). However, no certification crash tests have been carried out for this system. Strong-post W-beam barriers are widely installed in the states of Victoria, Queensland and South Australia where 6 mm thick 178×76 mm cold rolled channel steel posts and blocks, spaced at 2500 mm are used (Vicroads, 1997; Grzebieta, Zou, Corben, Judd, Kulgren, Tingval and Powell, 2002).

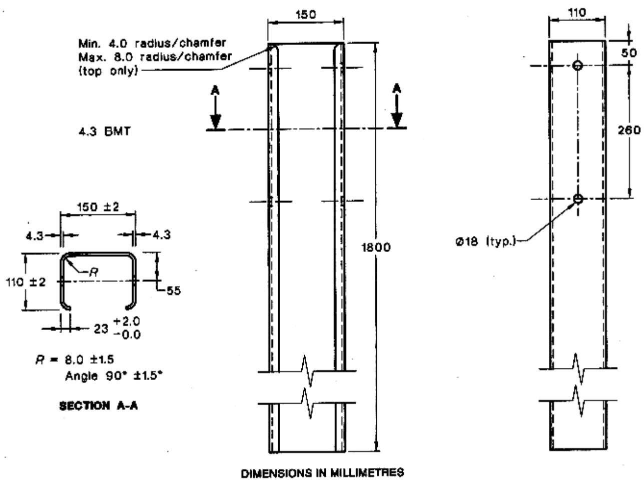

Figure 3 Strong-post W-beam barrier recommended in AS/NZS 3845

In Australia barrier specification can be confusing. AS3845 [3], AS 1742.3 [4] and AS 5100.2 [5] are the standards that specify how permanent and/or temporary barriers are to be designed, used or tested for roadside and bridge barrier systems. However, each state regulatory authority also has its own road design guidelines that further complicate barrier specifications.

In Europe, W-beam barriers are different from those used in the USA and Australia. The W-beam rails are essentially the same, but the posts and blocks are quite different. Barriers should comply with European Standard EN1317-1 & 2. Five millimetres thick 100×50 mm and 4 mm thick 120×55 mm C-shaped steel are used for posts. A variety of blocks are used and mounted in different manners (Fattorini and Fernandez, 2000; Vesenjak and Ren, 2002). The typical post spacing is also 2000 mm.

Wire rope barriers

Another form of barrier that is now beginning to be used widely because of its good crashworthiness features for cars is the wire rope barrier. Two forms have been used in Australia since 1992; the Brifen system and the Flexfence system (VicRoads, 1998). Wire rope barriers are also used in Europe and the US. Figure 4 shows two systems currently used in Australia. Both are made from 4 wire ropes that are maintained in position and are placed under tension.

The key feature of wire rope barriers is that when a vehicle strikes them, the deceleration is low enough during the redirection process that the airbags do not trigger. Hence, such barriers are being referred to as flexible systems.

Figure 4 Left: Brifen system tested at Monash. Right: Flexfence system

Figure 5 Wire-rope underide (after Owen, 2005)

Statistics both in Australia and Sweden are highlighting their excellent crashworthiness characteristics particularly on rural roads and freeways (Larsson et al, 2003) with as much as 90% reduction in fatalities wherever they are installed. However, despite this good record, there are still some contentious issues regarding the use of such systems. The first concerns motorcycle safety which is discussed in another ESV paper (Berg et al, 2005). The second issue concerns vehicles under riding the wire ropes (Figure 5) for various reasons including inadequate rope tension because of poor maintenance and/or installation. The third issue concerns whether such barriers can adequately redirect rigid and articulated trucks. However, this last concern also applies to both W-beam and medium height concrete barriers.

Temporary plastic barriers

Temporary barriers for use in protecting workers in road works are made from concrete, steel and more recently from plastic polymers (Carey and Grzebieta, 2004). Polymer water-filled modules were first seen in Europe as channelling devices during the Tour de France in the 1980's. They were first introduced into Australia in the early 1990's. Later modules soon followed with an increased physical size and a variety of interlocking joining mechanisms. The profiles were generally based on the New Jersey concrete road barrier shape.

Figure 6 Waterfillable Roadliner barriers tested and certified to AS/NZS 3845.

Their lightweight portability became the feature of these systems. Water ballast could be added to the modules to increase mass and the water then dumped when the system needed to be relocated.

The visual appearance of plastic systems gave rise to the perception that when impacted they would redirect errant vehicles in a similar manner to temporary concrete structural barriers. This turned out to be quite misleading and more recently has resulted in fatalities on Australian roads where non-certified units were struck.

In 1988 the French Company Sodirel impacted their system with a 1250 kg vehicle to ER DPS134 and took their product to Canada at the same time as the Matsuta modules from Israel were informally tested in the United States.

Both the US and Canada used NCHRP 350 as the testing benchmark for plastic road barrier systems. Neither of these products could meet the first part of the Level 1 test criteria.

US companies at this time (1995) had designed plastic water ballasted barriers that met level 2 two (2) of the NCHRP350 longitudinal barrier test. Hence, the descriptive term adopted for NCHRP350 compliant systems in Australia became "safety barriers".

The importation cost of plastic "safety barriers" was high as these products were engineered with steel internal frames or external saddles and certified to NCHRP 350. They were thought to be clumsy and extremely expensive compared to the European lightweight modules then appearing in Australia and elsewhere in the world.

In the early nineties all manner of road furniture items were in use in Australia; painted 44 gallon drums, timber barrier boards suspended between steel trestles, lengths of guardrail bolted to steel stakes and drums, etc. Contractors fabricated home brew devices from any materials at hand and were delighted when plastic barrier like units made their way into the hire company's inventories.

These new devices could be set up in a myriad of configurations and had stanchion apertures as well as water filling holes from which various fences and signage could be suspended. In fact, these devices became the universal fixit for contractors. Certainly they were highly visible from long distances, commanded the attention of drivers and were perceived to be safety devices.

For a long period there was no challenge to these devices because Australian State road authorities initially ignored their deployment. After numerous complaints directives were issued by regulators advising where safety barriers should be used and requiring the marking of non-compliant units with the instructions "NOT TO BE USED AS A SAFETY BARRIER". Advice was also issued to manufacturers that such units must meet the NCHRP350 traffic device test 70/71 if they were to be used to channel traffic. These directives only now are slowly being enforced.

In 1999 Standards Australia published AS/NZS 3845 "Road safety barrier systems". The committee implementing this standard when examining the issue of plastic water filled safety barriers added an additional Level 0 (820 kg vehicle at 50 km/hr and at 20º and 1600 kg vehicle impacting at 50 km/hr at 25º) to the test Matrix with the intention of setting a minimum credential requirement for all plastic barriers at roadwork sites.

CRASH TESTS

Monash Crash Test Series

A series of small car crash tests into roadside barriers were carried out by the Department of Civil Engineering, Monash University with Swedish and Australian sponsors at a decommissioned airforce base at Laverton near Melbourne in Victoria, Australia. Wire-rope, W-beam, Concrete median barriers and a Pipe-fence system were tested.

The testing included development of a remote control system, vehicle preparation and data logging. High-speed cinematography was carried out by Autoliv Australia.

A Toyota Echo was chosen as the test vehicle. The crashworthiness of this vehicle was at the time of testing ranked as the 2nd best in the world for a small car according to NCAP (New Car Assessment Program) tests. Two crash tests were carried out (80 km/hr at an impact angle of 45º and 110 km/hr at 20º) as indicated in Table 1.

A general description of the car setup, remote control system, data acquisition system, dummies and barrier test layout and general overview of the test outcomes including the crash pulses (see also Figure 19) are provided in other earlier papers (Corben et al, 2000, Ydenius et al, 2001, Grzebieta et al, 2002). What is highlighted here are some of the outcomes that are relevant to improving the crashworthiness of vehicles and barriers for designers and manufactures.

Rigid concrete barrier

What is most evident from the crash tests is that the pretensioners and airbags will more than likely fire and the vehicle undergoes significant damage to steering when the vehicle strikes the barrier. This will be the case for any crash into any type of rigid concrete barrier be it a Jersey, F shape, Constant slope barrier or vertical barrier, where impact speed exceeds around 60 km/hr and the impact angle is equal to or greater than 20º.

Impact forces can now be predicted with reasonable accuracy and hence average decelerations can be obtained for designers of both barriers and airbag systems so long as the crush characteristics of the vehicle are known (Jiang, Grzebieta & Zhao, 2004).

Jersey and F shape barriers will launch vehicles into the air and more than likely result in a vehicle rollover if struck at larger angles. Figure 7 shows the small car (Table 1) impacting the barrier at 80 km/hr at 45º. The crash was not survivable with large intrusion into the vehicle cabin and roof crush as shown in Figure 8. Figure 9 shows how the vehicle launches in the air at 110 km/hr at 20º impact angle. The dummy's head is thrown towards the side window and the passenger's head strikes the shoulder of the driver. The dummy kinematics is a combination of a frontal offset crash and a near side impact crash for the passenger and a far side impact for the passenger. Side air curtains would provide benefit in such crashes but a frontal airbag firing would hinder recovery.

Whilst there is a higher risk of rollover with the Jersey barrier than with the F shape barrier, Sicking has pointed out at a recent NCHRP 350 meeting (2004), the risk of rollover for these barriers is around 2.3 times greater for both barrier types than for a vertical barrier. Figure 10 shows how a pick up rolls over when hitting F-shape temporary and rigid barriers.

Car manufacturers need to consider how best to protect occupants in such crashes. Barrier manufacturers need to consider Sicking's (2004) proposal of manufacturing vertical wall barriers.

The main issue with rollover is that presently there are no suitable design rules that protect vehicle occupants in rollover crash anywhere in the world. FMVS216 has been shown to provide inadequate protection by Friedman and Nash (2001). This issue is further discussed in the section dealing with wire rope barriers.

Guardrail barrier

The guardrail test with the vehicle striking the barrier at 110 km/hr at 20º resulted in a low deceleration crash. The airbag did not fire and the vehicle was brought safely to rest in a controlled manner. The barrier dissipates energy by movement of the posts in the soil sideways. The blocks shown in Figure 2 help keep the vehicle's tire from interacting with the posts and possibly cause the vehicle to roll over. However, research work presently being carried out to determine equations for predicting working width, impact loads and the minimum post spacing required that ensures smooth redirection (Jiang, Grzebieta & Zhao, July 2004), has revealed that posts that are concreted into the pavement as shown in Figure 11 will cause the impacting vehicle to rollover. This practise of concreting the posts is common and highlights a problem of systems being installed by contractors that have little understanding of how such barrier systems redirect vehicles.

An interesting result was obtained with respect to the 80 km/hr at 45º impact test into the guardrail system. The vehicle "pocketed" into the barrier rather than being redirected. The front right wheel also under-rode the barrier and was torn from the vehicle during rebound as shown in Figure 12. What was revealed was the barrier was incorrectly installed by the contractor in that it was missing end

Figure 7 Impact of Echo into New Jersey barrier at 80 km/hr and 45º.

Figure 8 External and internal crush deformation for 80 km/hr at 45º impact into concrete barrier.

Figure 9 Impact at 110 km/hr at 20º.

Figure 10 Top: F shape moveable, Chevy C-20 at 99.4 km/hr and 26.4º Bottom: F shape fixed, Chevy ¾ ton at 99.8 km/hr @ 25.3º (after Sicking, 2004).

Figure 11 Guard rail barriers. Left: posts move in soil. Right: post set in concrete.

cables that provide further tensioning of the guardrail. Nevertheless it was felt that this would not have significantly altered the test outcome. The major issue was that the tyre under-rode the barrier. Hence barrier height is important and variation in wheel diameters needs to be considered by both vehicle and barrier manufacturers.

Whilst the crash was survivable it did fire the airbag. Moreover the firing of the airbag occurred when the head was already close to the steering wheel as shown in Figure 13. Details of the trigger timing for both the seat belts and airbags are published elsewhere (Grzebieta and Zou, 2001, Grzebieta et al, 2002). It is also worth noting that the head was guided towards the A-pillar both by inertia and by the airbag. Impact of the head with the airbag is similar to an out-of-position occupant situation.

Figure 12 Pocketing and under-ride into guardrail barrier – 80 km/hr at 45º.

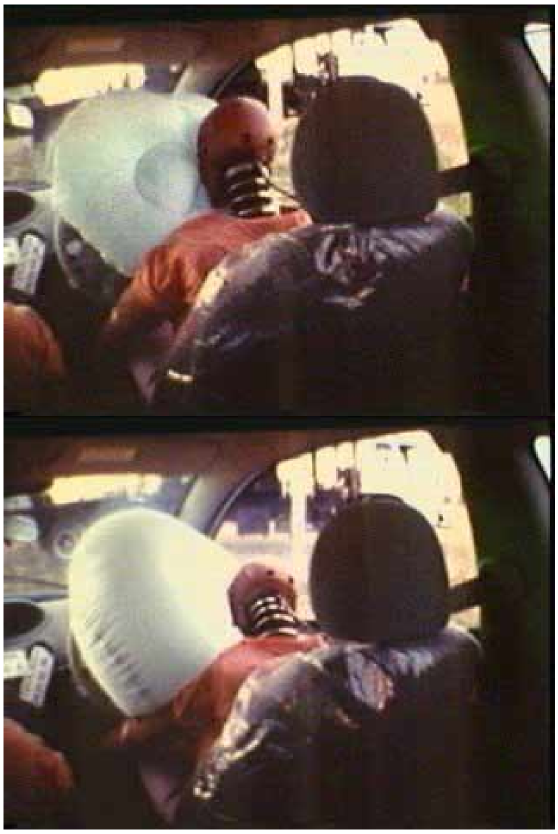

Figure 13 Top: airbag not fully inflated. Bottom: at full inflation.

<u>Wirerope barrier</u>

In the impact with the wire rope barrier at 110 km/hr at 20º the vehicle rolled over. The cause of the rollover was considered to be due to the shortness of the wire rope barrier which was tensioned to specification. Hence care needs to be taken in ensuring wire rope barriers are not only of adequate length but also set up exactly in the configuration as they were tested and certified.

An interesting outcome from the rollover crash was the on board image of the roof crushing onto the dummy head as shown in Figure 14. This high speed film captured the moment when the neck of the

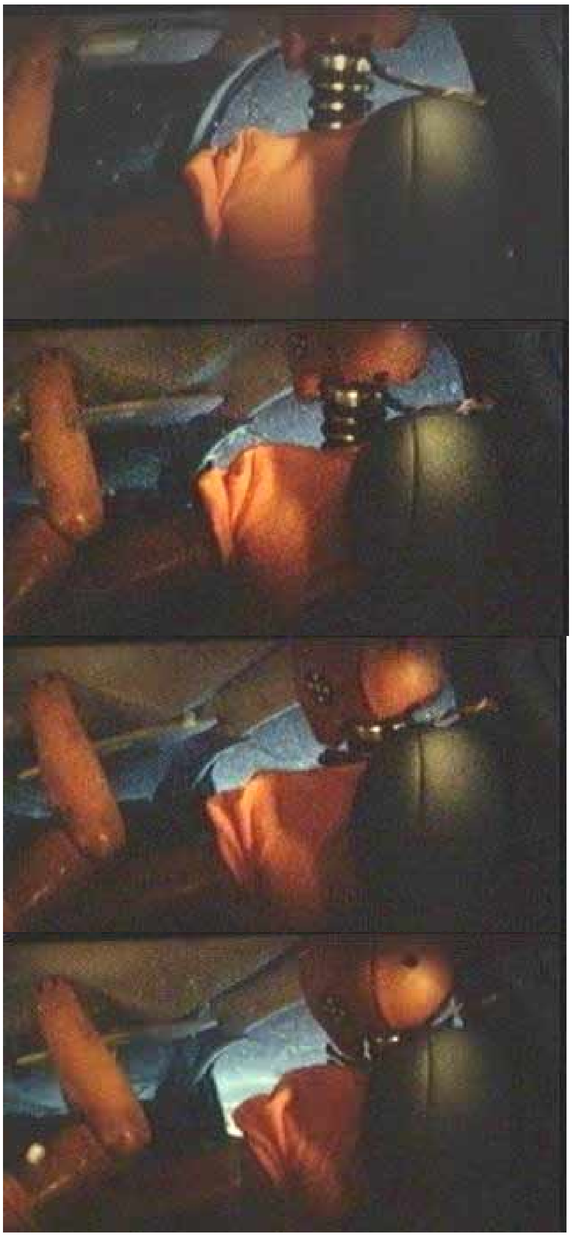

Figure 14 Roof crush in rollover compresses neck.

Hybrid III dummy is loaded and deforms into an S shape providing further good evidence of how roof crush in a rollover event can lead to either a fatality or serious neck injury where paraplegia or quadriplegia would occur. Rechnitzer et al in their study of serious neck injuries in rollover crashes pointed to the issue of roof crush as the main contributor to such injuries in 1998. The vehicle deformation shown in Figure 15 from both the Monash crash test and the vehicle shown in their paper, illustrating how an Australian football celebrity died in a rollover crash, are notably similar.

Temporary water filled barriers

A second series of crash tests were carried out at Monash University during development of roadside temporary barriers. Figure 16 shows a small compact car striking a water filled plastic barrier at 50 km/hr at 20º that replicates the Jersey Barrier shape and is commonly used as a delineator. The vehicle rolls on its side during redirection. In another crash a sedan vehicle of 1600 kg mass was made to strike a similar shape water filled barrier from a different manufacturer at 50 km/hr and at 25º. The vehicle climbed over the top of the barrier and down onto the road on the other side of the barrier line at the same angle it was travelling towards the barrier line. In other words, it was as if the barrier line did not exist, and the vehicle was not redirected.

The barriers shown in Figure 16 were redesigned to those shown in Figure 6. These barriers passed the Level 0 test as detailed previously.

The barriers were further redeveloped to those shown in Figure 20. A guardrail was attached to the front of the barrier in order to provide bending capacity and resistance to barrier perforation. A sub compact vehicle, a 2002 Daihatsu Cuore was chosen so that the compliance mass of 816 kg specified in

Figure 15 Top: Damaged profile of vehicle from the Monash Series wire rope crash test. Middle and bottom: Similar crush profile and injury mechanism presented by Rechnitzer et al (1998).

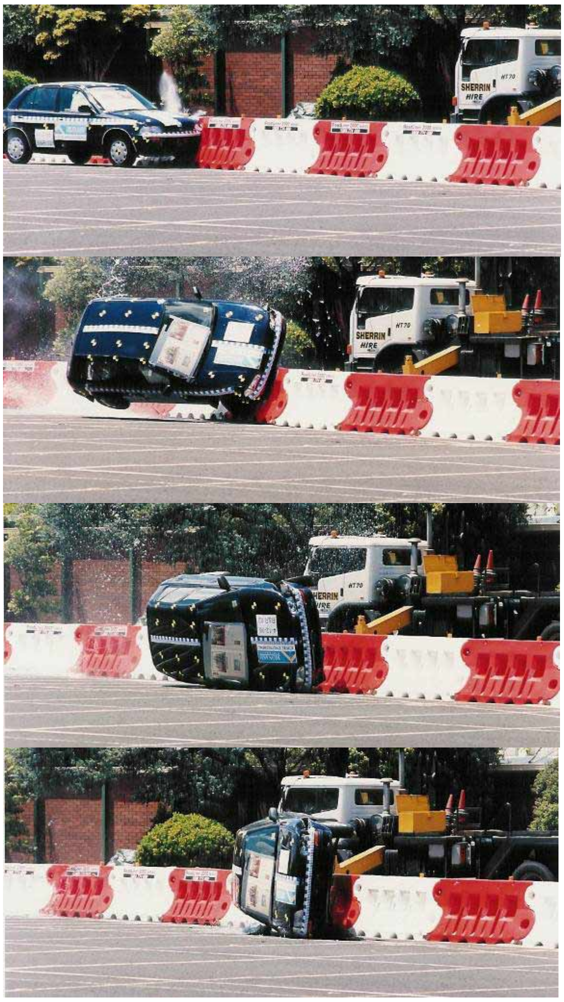

Figure 16 Small car impact into plastic delineator barrier.

NCHRP 350 could be met. Finding a sub compact vehicle that is light enough to meet this requirement is very difficult. Hence the more recent changes to vehicle masses proposed in updates to NCHRP 350. Most common compact vehicles weigh in at around 1000kg kerb mass.

Vehicles of this light mass usually have a short front end. This leads to climbing of the vehicle's struck side because there is insufficient crush distance between the front wheels and the bumper bar and the axle distance is short. It is for this reason the Ford Festiva with its longer front end/bonnet was used to certify most recent US barriers despite being an old outdated vehicle that in reality long ceased to represent the modern US compact car fleet.

Another issue with the smaller sub compact car is that the front bumper, radiator, lights and mudguard (fender) is much softer than the engine rail. The vehicle is fitted with an airbag to comply with frontal offset crash standards. Figure 17 shows the results of the Level 2 Daihatsu impact at 70 km/hr at 20º. However the stiffer engine rail acts like a spear perforating the barrier as shown in Figure 18. The guardrail helps restrict the intrusion and snagging to some degree. The tyre under-rides the barrier, tearing the wheel in a manner somewhat similar to the crash test shown in Figure 12. Again this highlights the need for both barrier manufacturers as well as vehicle manufactures to be aware that smaller diameter wheels can lead to inappropriate snagging problems where guardrail terminals are used.

The deceleration during impact in the Daihatsu crash test (Figure 17) was low enough that the airbag did not trigger. Whilst the engine rail tore the plastic wall the vehicle continued sliding along the barrier line where the average deceleration was around 7 g's.

Figure 17 NCHRP 350 Level 2 (70 km/hr at 20º) barrier crash test involving a Daihatsu car.

Figure 18 Tears in barriers caused by engine rail spearing through plastic.

Figure 20 shows the 2000 kg vehicle impact test at 25º. In this instance the vehicle did not snag. Nor did an engine rail protrude. The barrier redirected the vehicle along the barrier line so that a wave formed in front of the barrier and the vehicle was brought to a controlled slow stop. This is how barriers should ideally react. The airbags did not deploy and the vehicle could be driven away. Again the flexibility of the barrier system resulted in a redirection that did not lift or overtly damage the vehicle and hence would place any occupants at risk.

The vehicle crash pulses from the Level 2 barrier tests are compared to the vehicle crash pulses from the earlier Monash series tests in Figure 19. The crash pulse for the small vehicle (Figure 17) was equivalent in severity to striking a ductile W-beam barrier and for the 2000 kg vehicle the deceleration was even lower.

REAL WORLD EXAMPLES AND CONCLUSIONS

Figure 21 shows a small selection of roadside hazards that typify the problems encountered in regards to road design that the authors have noted and that persist despite available crash test evidence for many years that when vehicles strike such hazards the risk of a fatality or serious injury is high. The pictures are as follows; Frame A: Perth

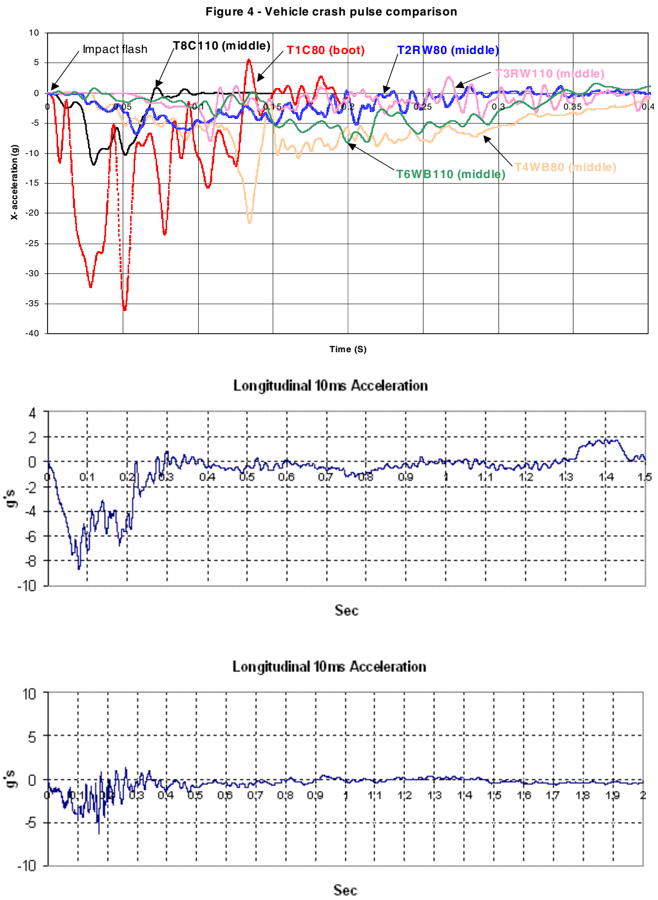

Figure 19 Vehicle crash pulses from Monash test series: (top graph) where C=concrete (Figure 7), WB=W-Beam (Figure 12), W=wire rope (Figure 4 & Figure 15) and speed is 80 or 100 km/hr (see Grzebieta et al 2002 for details); and from water filled Level 2 barrier tests (middle graph is small car in Figure 17, bottom graph is pickup truck in Figure 20)

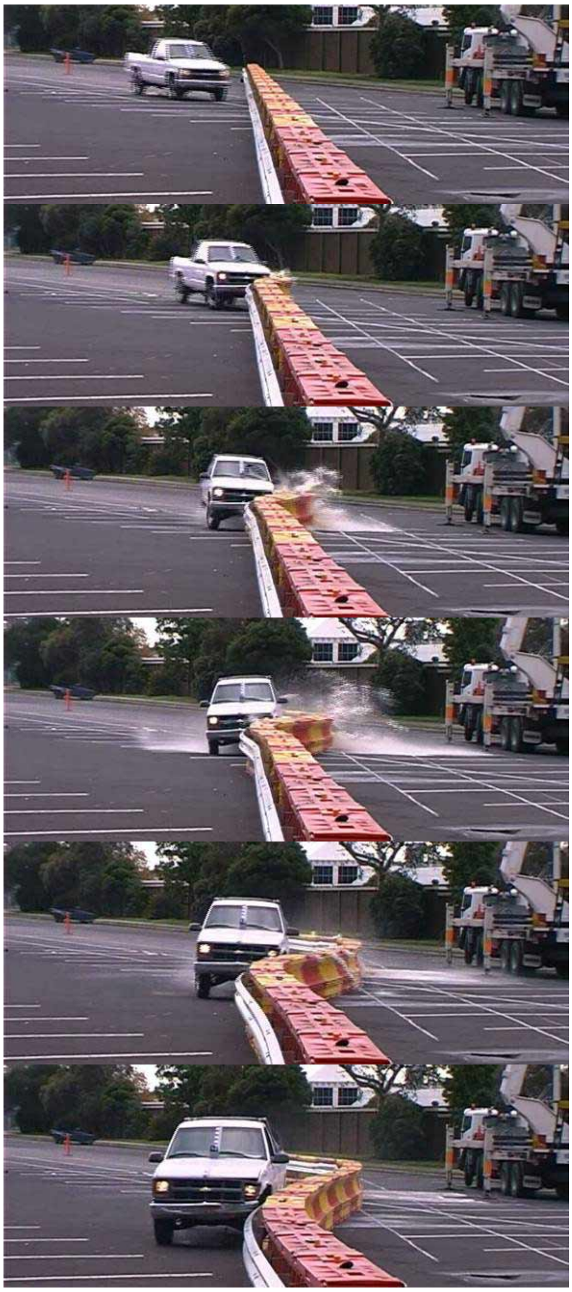

Figure 20 Crash test of 2000 kg US pickup truck impacting barrier at 70 km/hr at 25º.

freeway, B: Melbourne 100 km/hr new freeway, C: Melbourne exit ramp from new freeway, D: Melbourne concrete F shape barrier on 100 km/hr new freeway where wheel imprints are visible, E bridge pier in 100 km/hr zone in Wellington New Zealand with 70 km/hr speed limit zone placed 50 meters past the pier. What is of particular concern is the proliferation of hazards on completely new freeways where a large number of road safety audits have already been carried out.

These selected examples and the crash tests described above demonstrate that road and vehicle engineers must begin to work together such that information regarding vehicle crash behaviour

Figure 21 Real world lethal roadside hazards in Australia and New Zealand.

flows freely between the two disciplines. Such an initiative has already started in Australia with the formation of the Australasian College of Road Safety and the Australian Automobile Association's "SaferRoads" program (see www.acrs.org.au & http://www.aaa.asn.au/saferroads/ & ACRS 2004 Year book). It is clear that government authorities responsible for road safety such as NHTSA and FHWA and similar bodies in other countries can no longer work as separate entities if the road toll is to be dramatically reduced over the next decade.

Another issue critical to further reducing road trauma in different countries is increasing funding to investigate the crashworthiness of roadside barriers via fully instrumented crashes. Whilst considerable resources are available to study instrumented car crashes, the same magnitude of resources are not available to determine how best to design roadside barriers. This is particularly so in relation to trucks impacting barriers. Only a few crash tests of large trucks impacting barriers have been carried out and yet millions of these vehicles transporting goods travel the roads of the world intermixing with cars.

REFERENCES

AASHTO (2002), "Roadside Design Guide 2002", American Association of State Highway and Transportation Officials, Washington, D.C.

ACRS, (2004) "Yearbook of the Australasian College of Road Safety - Road Safety Towards 2010", www.acrs.org.au/srcfiles/2004yearbook.pdf.

Beason, W. L. (1989). "Single-Slope Concrete Median Barrier". Transportation Research Record No. 1302. Washington, D.C., Transportation Research Board, National Academy Press.

Beaton, J. L. (1956). "Full Scale Tests of Concrete Bridge Rails Subjected to Automobile Impacts". Proceedings of the 35th Annual Meeting of Highway Research Board: pp. 251-267.

Berg A., Rücker P., Gärtner M., König J., Grzebieta R. & Zou R., "Motorcycle impacts into roadside barriers – real-world accident studies, crash tests and simulations carried out in Germany and Australia", Proc. 19th ESV, Paper Number 05-0095, Washington DC, June 2005.

Buth, C. E., Hirsch, T. J. and McDevitt, C. F. (1990). "Performance Level 2 Bridge Railings". Transportation Research Record No. 1258. Washington, D.C., Transportation Research Board, National Academy Press.

Carey A and Grzebieta R., New generation water-filled barriers promote safety, Roads, Hallmark Editions, April/May 2004.

Corben B., Grzebieta R.H., Judd R., Kullgren A., Powell C., Tingvall C., Ydenius A. and Zou R., Interactions between guardrails, cars and passive safety systems, Proceedings Road Safety Research, Policing and Education Conference, CARRS-Q, QUT, Brisbane, pp. 643-648, 2000.

European Standard EN1317-1 & 2, Road restraint systems - Part 1: Terminology and general criteria for test methods, Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers, European Committee for Standardization (CEN) Brussels, Belgium, 1998

FEMA (2000), Final Report of the Motorcyclists & Crash Barriers Project, The Federation of European Motorcyclists Associations, Brussels, Belgium.

Friedman D. and Nash C., Advanced roof design for rollover protection, Proc. 17th ESV, Paper No. 01-S12-W-94, Amsterdam, Netherlands, 2001.

Grzebieta R.H. and Zou R., Report on Road Side Barrier Crash Tests, Monash University, August, 2001.

Grzebieta, R. H., Zou, R., Corben, B., Judd, R., Kulgren, A., Tingval, C. and Powell, C. (2002), Roadside Crash Barrier Testing. International Crashworthiness Conference - ICrash2002, Melbourne, Australia.

Hellmich, K. (2002), Road Restrain Systems with Higher and Very High Containment on Bridges. IABSE Symposium 2002, Melbourne, Australia.

Hirsch, T. J. (1986). "Longitudinal Barriers for Buses and Trucks". Transportation Research Record No. 1052. Washington, D.C., Transportation Research Board, National Academy Press: 95-102.

Jiang T., Grzebieta R. H. and Zhao X. L. Predicting impact loads of a car crashing into a concrete roadside safety barrier, Int. J. of Crash.,Vol.9 No. 1, 2004.

Jiang T, Grzebieta R H, Zhao X L, Impact Performance of W-Beam Safety Barrier Systems Proceedings ICRASH 2004 International Crashworthiness Conference, San Francisco, July 2004.

Larsson, M., Candappa, N.L., and Corben, B.F., Flexible Barrier Systems Along High-Speed Roads – a Lifesaving Opportunity, Monash University Accident Research Centre Report No 210, 2003.

Mak, K. K., Gripne, D. J. and McDevitt, C. F. (1995). "Single-Slope Concrete Bridge Rail". Transportation Research Record No. 1468. Washington, D.C., Transportation Research Board, National Academy Press.

Menges, W. L., Buth, C. E., Bullard, D. L. and McDevitt, C. F. (1995), Performance Level 3 Bridge Railings. The 74th Annual Meeting, Transportation Research Board, Washington, D.C.

Michie, J. D. (1971), NCHRP Report 115: Guardrail Performance and Design, Highway Research Board, National Research Council, Washington, D.C.

Neol, J. S., Hirsch, T. J., Buth, C. E. and Arnold, A. (1981). "Loads on Bridge Railings". Transportation Research Record 796. Washington, D.C., Transportation Research Board, National Academy Press.

Owen T. S., Wire Rope Crash Control Barriers, Technical Rescue, 41-Summer 2004, http://t-rescue.com/articles/crash_control/.

Plaxico, C. A., Ray, M. H. and Hiranmayee, K. (2000). "Comparison of the Impact Performance of the G4(1W) and G4(2W) Guardrail Systems Under NCHRP Report 350 Test 3-11 Conditions". Transportation Research Record, Paper No. 00-525. Washington, D.C., Transportation Research Board, National Academy Press.

Ray, M. H. and McGinnis, R. G. (1997), NCHRP Synthesis 244: Guardrail and Median Barrier Crashworthiness - A Synthesis of Highway Practice, Transportation Research Board / National Research Council, National Academy Press, Washington, D.C.

Rechnitzer G., Lane J., McIntosh A.S. & Scott G., Serious neck injury in rollovers – is roof crush a factor? International Journal of Crashworthiness, V3 No.3, Woodhead Publishing, Cambridge, U.K. September, 1998.

Ross, H. E., Zimmer, R. A. and Michie, J. D. (1993), NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features, Transportation Research Board / National Research Council, National Academy Press, Washington, D.C.

Sicking D.L, Why Do We Continue To Build Safety Shape Barriers?, Midwest Roadside Safety Facility, TRB AFB20 Summer Meeting, Workshop on the update to NCHRP Report 350 and current safety issues, Overland Park, KS, July 2004.

Standards Australia, AS 1742.3: Manual of uniform traffic control devices Part 3: Traffic control devices for works on roads, Standards Australia, Sydney, ISBN 0 7337 4845 7, 2002.

Standards Australia, AS/NZS 3845 Australian / New Zealand Standard for Road Safety Barrier Systems, CE/33 Committee, ISBN 0 7337 2293 8, 1999.

Standards Australia, AS 5100.2: Bridge design Part 2: Design Loads, Standards Australia International, Sydney, ISBN 0 7337 5628 X, 2004.

Troutbeck, R. J. (1975), ARR Report No. 45: A Review of the Literature of Full Scale Tests on Safety Barriers and Kerbs, Australian Road Research Board.

WPI (2004). Index of /Academics/Depts/CEE/Impact/Pix/barriers, Worcester Polytechnic Institute (http://www.wpi.edu/Academics/ Depts/CEE/Impact/Pix/SGR04/). 2004.

Vicroads (1997), Road Design Guidelines Part 9: Standard Drawings for Roadworks Version: 17 March 1997.

VicRoads (Road Safety Department). (1998). Flexfence Wire Rope Safety Rope Safety Barrier. Safe Roads, no.105.

Ydenius A., Kullgren A. & Tingvall C., Development of a crashworthy system: interaction between car structural integrity, restraint systems and guardrails, Proc. 17th ESV, Paper number:171, Amsterdam, Netherlands, 2001.