Designing and testing bollards to protect pedestrians

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Abstract

This is the second paper in a series of articles by the authors focussing on examples of how formalised Interface Analysis and Design methods can be applied to improve road safety across different road domains, in this case that of pedestrians and motorised vehicles. Bollards can be used as a barrier line against vehicle ingress in situations where traditional roadside safety barriers are not suitable and it is desirable to protect for example pedestrians on footpaths, roadside diners, people waiting at bus stops and tram stops, etc. Bollards provide a more slender protection line than traditional bulky roadside barriers and a means for pedestrians to readily pass through the protection line. They are most suitable in shopping precincts where there is high pedestrian activity and where protection is required to shield against an errant vehicle that can still legally move at speeds in excess of 30 km/h. A methodology for designing, testing and rating the crashworthiness of bollards is presented. Some examples of inappropriate and potentially dangerous roadside barrier installations to protect pedestrians that could be replaced by bollards, are shown. The paper further discusses the test protocol proposed for bollards in the revision of AS/NZS3845 Road Safety Barrier Systems. The conclusions are: a barrier system constructed from bollards can be designed and crash tests carried out to validate that they perform in a crashworthy manner at an affordable cost; the bollard foundation is critical to the performance of the bollard to resist impact loads; and the speed of cars need to be controlled in terms of impact speed so as not to exceed the bollard’s capacity.

Introduction

This is the second paper in a series of articles being published by the Authors presenting examples of how formalised Interface Analysis and Design methods can be applied to improve road safety across all domains (Grzebieta and Rechnitzer, 2013). The examples presented are based on the Authors’ experience investigating hundreds of crashes, carrying out road safety research, engineering design and applying system interventions. This paper focuses on the interface between the most vulnerable road user, namely a pedestrian, and a motorised vehicle (cars, buses, trucks, etc.).

Many hundreds of thousands of collisions occur in Australia each year. Based on data from the Bureau of Infrastructure, Transport and Regional Economics (BITRE), the result of the approximately 700,000 road crashes in Australia in 2011 was around 1,300 fatalities and 35,000 serious injuries (BITRE, 2012). The types and distribution of fatal traffic crashes including vulnerable road user collisions by road user category, indicate vehicle occupants (including heavy and light vehicles) make up 69% of the total, pedestrians 14%, motorcyclist 15% and bicyclists 2%. Last year in 2012 there were 174 pedestrian deaths which was down on the previous 2011 total of 185 but higher than the 2010 total of 170 (BITRE, 2013). The distribution of serious injury in 2008-2009 by road user type was vehicle occupants 35%, pedestrians 7%, motorcyclists 27%, bicyclists 18% (AIHW, 2012). It is interesting to note the significantly higher percentage of motorcyclist and bicyclists serious injuries compared to other road users. Figure 1 shows the distribution of pedestrian fatalities since 2000 for Australia. Whilst the trend from 2000 to 2010 was clearly downwards, the reduction in fatalities over the last three years has stalled.
Worthy of note is the introduction of a blanket default 50 km/h speed limit throughout Australia (in urban areas) by 2003 but in particular the effect it had in New South Wales (NSW). A 2009 study by Falster et al. (2009) of pedestrian injuries caused by motor vehicles in NSW indicated that pedestrian involved crashes accounted for around 16% to 18% of all NSW road-based fatalities in 1999/2000. At a particularly high risk of pedestrian injury are children, frail or older persons, and young adult males. They are consistently found to present the highest rate of mortality within pedestrian casualties (Falster et al., 2009, Frydenberg, 2012). To counter these higher numbers overrepresented by pedestrians in around 2000, the NSW government introduced initiatives to specifically address pedestrian safety. These initiatives included the introduction of a 50 km/h urban speed limit in July 1998 (leading to the enactment of the general urban speed limit of 50 km/h in November 2003), targeted driver awareness and public education campaigns focused on pedestrian safety, community based local council Road Safety Officer programs, the introduction of the 40 km/h reduced speed limit in local school zones which operated between 8 am and 9:30 am and 2:30 pm to 4 pm, and the introduction of a number of 40 km/h high pedestrian activity zones. Falster et al, (2009) presented in Figure 2 the rate of annual age-sex standardised rates of casualties, hospitalisations and deaths due to pedestrian injury in NSW for the years 1999-2007 for children, adults and older persons. It is clear that these measures have had a beneficial effect in reducing injuries overall. But again it can be seen these reduction appeared to stall at around 2007.
Further recent work by Frydenberg et al. (2012) investigating differences between road user groups, mortality rates and pattern of injuries in 5118 trauma presentations to the St George Public Hospital (SGH) from January 2002 to June 2008 that were prospectively collected, indicates that vulnerable road users have a significantly higher mortality rate than other road users. They evaluated injury severity and patterns using the Injury Severity Score (ISS), the New Injury Severity Score (NISS) and the Abbreviated Injury Score (AIS). Multiple regression analysis was used to analyse data. Frydenberg et al. (2012) found the risk of death was 5 times higher for injured pedestrians than drivers and that patients with head injuries had an increased risk of death compared to patients without head injuries. They concluded that further research into factors contributing to pedestrian injury such as road design and pedestrian crossings was needed.

One system of better protecting pedestrians at different locations is to use crashworthy bollards. In a Safe System Approach (Mooren et al, 2011 and Grzebieta et al, 2012) both the pedestrian being protected and the occupants in the errant vehicle that impacts the bollard need to be protected. Prior to the introduction of the Safe System Approach, engineering design of road infrastructure (e.g. some safety barrier systems) tended to focus on protecting the at risk road user even if it could result in the driver and occupants of the errant vehicle being at risk of fatal or serious injuries. For example, Figure 3 shows a yellow concrete ramp end terminal used to protect commuters waiting for a tram.

All aspects of the Interface Analysis and Design (IAD) and the Safe System Approach were compromised in this crash. Firstly, the vehicle was likely travelling too fast given the design of the end concrete ramp. It was well known among roadside barrier designers that such ramps can launch vehicles unless the speed is kept very low at around 30 km/h. Similarly, where there is a likelihood
of pedestrians converging in an area, i.e. crossing to the tram stop, the speed needs to be set at a collision limit of around 30 km/h which is survivable (OECD, 2008). Secondly, once the vehicle launched, the survival of the vehicle occupants heavily relied on the strength of the roof. However, prior to recent times, it was well known that vehicle roof strength was low; in effect most vehicles possessed defectively low roof strength. The consequences of using such incompatible interfaces, i.e. the combination of vehicle speed where the kinetic energy is high, a poorly designed barrier and a defective roof with low strength, where all the “holes line up” in Reason’s (2000) Swiss cheese model, resulted in the death of the driver (Grzebieta et al, 2007).

Another example where the use of a roadside barrier is inappropriate is shown in Figure 4. While the barrier was likely installed to protect waiting bus commuters it has resulted in presenting a potential sharp edge hazard to pedestrians and cyclists alike. Moreover, the end of the barrier has been treated with what appears to be an energy absorbing ET 2000 end terminal to prevent spearing in the event of a motorised vehicle striking the end of the barrier. However the yellow portion of the terminal further presents a sharp protrusion hazard to motorcyclists and bicyclists. This barrier in almost every aspect fails the Interface Analysis and Design (IAD) considerations. The Authors also note concern with the use of such shared bicycle and cyclist footpath as this represents another IAD risk, i.e. collisions of bicyclists with pedestrians (see Short et al, 2007). An alternative substitute protection system could be installation of smooth rounded bollards to protect the bus commuters while at the same time reducing trip or collision hazard for pedestrians and cyclists.

Crash severity for occupants of a vehicle striking a bollard will depend on the combined crashworthiness performance of the bollard being impacted and the vehicle impacting the bollard. The bollard needs to prevent vehicle ingress up to a certain limit, i.e. around 0.5 metres, after which the bollard should not yield or allow the vehicle any further intrusion into the pedestrian environment, nor should it result in the vehicle rolling over. Moreover, the vehicle needs to be brought to rest or redirected over a reasonable distance which does not overtly decelerate the occupants restrained in the vehicle. An example of how safety bollards provide a segregated space...
for pedestrians is shown in Figure 5. However, these bollards are not necessarily designed in a crashworthiness sense to prevent vehicle ingress. On the other hand, Figure 6 shows a protected space for pedestrians at tram stops in Melbourne where the bollard acts as a crashworthy barrier. Pedestrians can move freely between the bollards. The bottom image in Figure 6 shows how a channelling effect narrowing the road down to one lane has been designed so that it naturally will slow a driver down to a safe speed limit.

In summary bollards can be used for a variety of reasons including:

- to inhibit access by vehicles into restricted trafficable roadways and pedestrian areas;
- to prevent ingress of an errant vehicle into a protected area by providing positive passive protection in the form of a road safety barrier to pedestrians in areas such as shopping strips, roadside dining areas, bus stops, tram stops, and areas of high pedestrian activity;
- to provide a barrier to an errant vehicle against striking a roadside hazard and by doing so protect the occupants in the vehicle;

Bollards can be used in situations where roadside barriers or crash cushions is inappropriate because of space limitations, pedestrian accessibility and aesthetics. They also have the potential of being used in place of a roadside barrier as an economical alternative. In general Bollards and Bollard Arrays that act to prevent vehicle penetration are non re-directive devices (or cushions).

Another way bollards can be used is as a bollard array. For example, the line of bollards shown in Figures 5 and 6 could be considered as a bollard array. Another novel way of using an array of bollards could be to progressively increase their energy dissipating capacity as indicated in Figure 7 as the vehicle ingress further towards the hazard.

Depending on the impact angle of the errant vehicle the bollard array can be struck such that:

- only a single bollard is struck;
- more than one bollard is struck at the same time; and
- bollards are struck sequentially one after the other
Figure 5: Traffic bollards segregating pedestrians while at the same time allowing pedestrians to move freely across the roadway.

Figure 6: Bollards protecting pedestrians waiting at a tram stop. Compare to Figure 3.

Bollard array protecting hazard. Larger energy dissipating bollards at rear and smaller energy dissipating bollards at front.
Figure 7: Bollard array protecting roadside hazard.

Reduction of the bollard pitch spacing, would dissipate the energy to more than one bollard and hence enable smaller individual bollards to be used as an array. A linked system in which individual bollards act together (similar to a stage system characteristic of some crash attenuators) could reduce the size of individual bollards. This has the advantage in that it would reduce the individual size of bollard foundations and therefore enable the development of a range of products for different applications.

If a single standalone bollard is hit without any load sharing capability, it is proposed that the bollard should be capable of withstanding the impact of the test vehicle and restrict the vehicle to no more than 0.75 metres penetration past the protection line.

Bollards and bollard arrays can also be used as a Barricade. Such systems may not necessarily bring a vehicle to a controlled stop but may instead gate, allowing the vehicle to continue past the barricade. In these circumstances the bollard system must be tested to ensure that when they do fail, they do not penetrate or show potential to penetrate the occupant compartment or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Likewise the collision with the Bollards should not cause the vehicle to excessively roll, pitch or yaw in order to provide the driver every opportunity to regain control of their vehicle.

One of the main characteristics that govern the strength of bollards is the foundation to which the bollard is attached. It is critical that the bollard is properly secured to a concrete foundation. The most reliable method of establishing if a bollard has sufficient strength and performance to resist a vehicle impact is to carry out a test. The current AS/NZS3845 Road Safety Barrier Systems is being revised and will shortly be released for public comment. The following describes the essential elements of the tests being considered in order for a bollard system to be considered crashworthy.

Proposed Bollard Crash Tests

Whilst bollards are extensively used as traffic barricades there is no international or Australian or New Zealand (NZ) crash test standard to assess their crashworthiness. Consideration is being given to how the Australian/NZ test protocol for evaluating bollards can be made compatible with European and/or United States of America (USA) roadside barrier crash test standards and vehicles typically used in roadside crash barrier evaluations. Individual tests in these standards are designed to evaluate one or more of the principal performance factors: structural adequacy, occupant and road user risk, and post-impact behaviour of the vehicle. However, the main issues in regards to any crashworthiness test proposed in the case of bollards is that both the pedestrian being protected and the occupants in the errant vehicle that impacts the bollard need to be protected in accordance with the Safe System Approach. It should also be noted that in some locations bollards are used simply as vehicle barricades redirecting traffic and do not possess any design capacity to stop a car (e.g. Figure 5). Such bollards should not present a hazard to occupants inside an errant vehicle that strikes them.

Most vehicles today are now designed with crashworthy systems such as airbags, seat belt pre-tensioners and crumple zones. Pre-brake, where the vehicle recognises it is about to crash and thus brakes autonomously and faster than the driver to reduce crash severity, has been developed and is now starting to appear in some vehicle models.

Indeed the crashworthiness requirements set down in Australian Design Rule ADR 73/00 (2005) can be readily met at impact speeds of up to around 50 km/h in most modern cars when they impact an unyielding object, of reasonable cross section area. Narrow objects such as poles and non-energy absorbing bollards, could still present a risk to vehicle occupants at such a speed, and the necessary interface restriction would be to reduce the vehicle speed to approximately 30-40km/h.
Hence, a bollard that is rigid (set in an appropriate concrete foundation that prevents any significant movement) with no energy dissipating characteristics could well be suitable to protect pedestrians from impact by an errant vehicle but such bollards still need to be tested for bollard and foundation strength, and suitable vehicle speeds. A limitation to this is if the errant vehicle were to strike the bollard similar to a side impact (Richardson et al, 2006). The impact speed limit would then be of the order of around 25 km/h to avoid serious injury. For 30 km/h pedestrian zones this would be an acceptable limit.

Currently there is no specific standard for testing the crashworthiness of road and traffic bollards as opposed to security bollards. The Authors recommend that following USA and European barrier standards could provide a basis for developing a crash test protocol for bollards. The two key factors in such crash tests are the vehicle test mass and test speed.

In Australia roadside safety barrier systems have been designed in accordance with the USA National Co-operative Highway Research Program (NCHRP) Report 350 code. The test vehicle masses nominated in this code are the 820C (nominal mass of 820 kg) and the 2000P (nominal mass of 2000 kg) (Ross et al, 1993).

In the latest US roadside safety barrier standard, the Manual for Assessing Safety Hardware (MASH) (AASHTO, 2009) that is now superseding NCHRP 350, these vehicle test masses have increased. The test vehicles nominated are the 1100C (nominal mass of 1100 kg) and the 2270P (nominal mass of 2270 kg).

In comparison, the relevant European standards that could be used are: EN 12767 Passive Safety of Support Structures for Road Equipment – Requirements and Test Methods; and European Standard EN 1317-3 for crash cushions. The vehicle mass recommended from EN 12767 standard is 825 kg ± 40 kg. This would be equivalent to the NCHRP 350 code’s 820C vehicle. The European Standard EN 1317-3 for crash cushions however requires the test vehicle masses of 900 kg, 1300 kg, and 1500 kg depending on the crash test severity being considered.

In regards to the crash test speeds, these vary widely in the various standards. For the US codes MASH and NCHRP 350 the speed of impact is associated with a Test Level (TL) (Ross et al, 1993, AASHTO, 2009). Depending on the feature being evaluated, there are up to six test levels that can be selected. However, only the three lower speed variants are applicable to breakaway structures and energy absorbing devices (e.g. sign supports and crash cushions). In general, the lower test levels are applicable for evaluating features to be used on lower service/speed level roadways and certain types of work zones while the higher test levels are applicable for evaluating features to be used on higher service/speed level roadways or at locations that demand a special, high performance safety feature. Moreover, the US codes only consider breakaway and barricade systems. The only energy absorbing devices considered by these codes are crash cushions. Energy absorbing bollards could be hence considered as a non-gating crash cushion impacted at 0 degrees.

The European standard is more complex than the USA approach and provides an allowance for the amount of energy absorbed by the structure: High energy absorbing (HE) structures slow the vehicle considerably on impact (e.g., an energy absorbing bollard or a rigid bollard); Low energy absorbing (LE) structures measurably slow the vehicle but pose a much lower risk of injury to its occupants (e.g., an energy absorbing bollard); Non energy absorbing (NE) structures have negligible or nil effect on the speed of the vehicle (e.g., a breakaway bollard).

The most relevant crash test protocol for bollards in the USA codes would appear to be those being used for crash cushions. In Europe there are two possible codes, which however provide different test speeds.
In the USA codes the impact speeds for crash cushions are nominated as 50 km/h (TL 1), 70 km/h (TL 2) and 100 km/h (TL 3). The same test speeds are used for breakaway systems.

The test speeds in the European standard EN 12767 for support structures are the same as the USA codes. However, in EN 1317-3 dealing with crash cushions some of the test speeds are different: i.e. 50 km/h, 80 km/h, 100 km/h and 110 km/h.

In terms of test injury or severity criteria that need to be met for the European standards EN 12767 and EN 1317-3, the Acceleration Severity Index (ASI) and Theoretical Head Impact Velocity (THIV) scales and range depending on energy rating and occupant safety level demand, are used.

For the USA standard, the concept of a flail space is used where the ‘occupant flails’ within the vehicle. The flail space criteria is an Occupant Impact Velocity Limit of 9 m/s (preferable) and 12 m/s (maximum) for energy dissipating systems and 3 m/s (preferable) and 5 m/s (maximum) for breakaway systems. The Occupant Ridedown Acceleration Limits are 15 g’s (preferable) and 20 g’s (maximum) where 1g = 9.81 m/sec².

The USA codes also allow for a Hybrid III anthropomorphic crash test dummy (ATD) for frontal impacts. This sets a maximum Head injury Criterion, chest deceleration, chest deflection, and neck injury criteria (e.g., HIC36 < 1000, Chest acceleration < 60 g’s, Nij < 1).

The European and USA standards are not dissimilar in terms of the injury threshold criteria requirement considering they are based on human injury tolerance indices established internationally. For example, in Europe for occupants wearing safety belts, the generally used limit is 12 g’s in the frontal direction.

In addition to above crash test requirements, there are further performance requirements for a vehicle striking a crash cushion and/or break away system that would be relevant for an energy dissipating bollard, a rigid bollard or a breakaway bollard, for example:

- acceptable performance may be one of redirection, controlled penetration, or controlled stopping of the vehicle;
- the vehicle should not penetrate, under-ride, or override the bollard although controlled lateral deflection of the bollard is acceptable to a limit;
- detached elements, fragments or other debris from the bollard should not:
  - penetrate or show potential for penetrating the occupant compartment;
  - present an undue hazard to other road users, in particular to pedestrians;
  - block the driver’s vision or otherwise cause the driver to lose control of the vehicle;
- the vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.

The bollard test requirements are intended to be incorporated into the revised standard AS 3845.2 Australian Road Safety Barrier Systems and Devices. The main issue is which of the above outlined crash test criteria from USA and European standards can be adopted as a basis for the bollard test criteria to be incorporated into the Australian/New Zealand standard as neither the European or USA standards deal directly with roadside bollards. This is a whole new development for the Australian Standards Committee.
Conclusions

Pedestrian fatalities are reducing albeit recent reductions have stalled. Energy dissipating bollards offer a practical protective interface between pedestrians and motorised vehicles principally for lower speed roads in pedestrian environments. Most energy dissipating systems such as barriers and crash cushions are large and aesthetically imposing objects that can be hazardous to pedestrians, particularly W-beam steel barrier systems with jagged edges.

One alternative that has received little attention in terms of protecting pedestrians is the development of roadside bollards with rounded ends. Whilst bollards are extensively used as traffic barricades there is no international or Australian or New Zealand crash test standard to assess their crashworthiness. Moreover, novel ways of using bollards as energy dissipating devices that are an alternative to roadside barriers used to protect occupants of errant vehicles potentially striking a hazard, have yet to be fully developed and implemented in terms of an appropriate Interface Analysis and Design. This paper presents alternatives by which an IAD can be effectively carried out for such protection systems.

The Authors recommend that the following criteria be used for crashworthiness testing for protective bollards:

1. The USA MASH test vehicle masses of 1100C and 2270P;
2. Two test levels TL1 (50 km/h) and TL2 (70 km/h);
3. Injury criteria for vehicle occupants as per MASH criteria noted above.

There needs to be proper recognition that bollards need to be protective for pedestrians where there exists the significant risk of an errant vehicle colliding with a pedestrian. If bollards are to be truly effective in reducing pedestrian injuries they must be designed to be crashworthy and not simply used as cosmetic channelling/barricade traffic diversion devices.

References

American Association of State Highway and Transportation Officials (AASHTO), Manual for Assessing Safety Hardware (MASH), (2009).

Bureau of Infrastructure, Transport and Regional Economics (BITRE), (2009). Road deaths Australia, 2008 Statistical Summary BITRE, Canberra ACT.

Bureau of Infrastructure, Transport and Regional Economics (BITRE), (2012). Road deaths Australia, 2011 Statistical Summary BITRE, Canberra ACT.

Bureau of Infrastructure, Transport and Regional Economics (BITRE), 2013, Road deaths Australia, 2012 Statistical Summary BITRE, Canberra ACT.


EN 1317-3:2010 Road restraint systems - Part 3: Performance classes, impact test acceptance criteria and test methods for crash cushions, Comité Européen De Normalisation (CEN), Brussels.


