OBSERVATIONS ON PERFORMANCE CHARACTERISTICS OF PLASTIC WATER-FILLED BARRIER-TYPE DEVICES

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ABSTRACT

The Austroads National Safety Barrier Assessment Panel (ANSBAP), through its wider work in assessing roadside safety barrier products, has undertaken a review of the general performance characteristics of Plastic Water-Filled Devices (PWFDs). ANSBAP has considered the outcomes of crash test results conducted under generally accepted test standards such as AS/NZS 3845, NCHRP 350, MASH and EN 1317.

During this assessment of PWFDs, a range of behaviours has been observed including gating, capture and redirection and it is determined that these behaviours are a function of impact conditions.

Consequent shortcomings in the information available for design have been identified.

The observations of the ANSBAP are documented in order to improve understanding throughout industry of the observed performance characteristics of PWFDs.

It is intended that the availability of this information will facilitate appropriate design installations when using PWFDs.

INTRODUCTION

The Austroads National Safety Barrier Assessment Panel (ANSBAP), through its wider work in assessing roadside safety barrier products, has undertaken a review of the general performance characteristics of Plastic Water-Filled Devices (PWFDs). This review has been restricted to those products that were either already accepted by jurisdictions or were being put forward for acceptance as work zone safety barriers.

During this assessment of PWFDs, a range of behaviours has been observed including gating, capture and redirection and it is determined that these behaviours are a function of barrier structural design, length of installation and impact conditions. The ability of PWFDs to redirect impacting vehicles is limited to low impact severity and the presence of gating and capture make the devices problematic because of the extent of intrusion of the barrier into the work zone.

ANSBAP treats submissions from suppliers as Commercial-in-Confidence and as such this paper is restricted in its ability to provide information that is directly linked to a particular proprietary product.
WHAT IS A PWFD?

A PWFD is a relatively flexible barrier-like system typically comprising units approximately 2 m in length, 0.6 m wide and up to 1.0 m in height, frequently used in temporary work zones and other situations. Each unit has a shell made of plastic (commonly rotomoulded polyethylene) which is intended to be filled with water. The units are joined together, typically with a steel pin that allows some flexibility at the joint resulting in the PWFD forming a string or chain. Two examples of PWFDs that have been previously accepted in jurisdictions across Australia are depicted in Figure 1.

![Figure 1: Examples of Plastic Water Filled Devices](image)

PWFDs were first seen in Europe as channelling devices during the Tour de France in the 1980s. The profiles were generally based on the New Jersey concrete road barrier shape. They were first introduced into Australia in the early 1990s. Later modules soon followed with an increased physical size and a variety of interlocking joining mechanisms (Grzebieta et al. 2005).

Typically, units include some form of internal frame or other structural element to provide strength and/or to convey tension longitudinally to other connected units along the barrier chain. The US Federal Highway Administration (FHWA 2012) has indicated that water-filled barriers can be used if they have a ‘steel framework’ that has been accepted as ‘crashworthy’ to resist penetration. This restriction appears to be cautionary because PWFDs without this requirement have been observed to satisfy other test regimes and thus it can be inferred that performance of PWFDs is a function of the structural design of the unit.

WHY IS THIS BEING INVESTIGATED?

A longitudinal safety barrier is used either to shield an errant road user from a hazard or alternatively to shield an important commodity (impact with which would be intolerable to the community) from an errant vehicle. A vulnerably located preschool or critical energy infrastructure might be examples of the latter category. The major focus on injury shifts from the road user in the first case to the people (or object) being protected in the second.

In the context of a work site, a safety barrier is a physical barrier separating the work area and the travelled way, designed, as far as practicable, to resist penetration into the work site by an out of control vehicle. Penetration should be limited whether the vehicle is contained or not. Because of the likelihood of road workers being present behind a work zone barrier, the risk of breach of the barrier or significant deflection of the barrier is arguably less tolerable than for a conventional barrier shielding a non-human hazard.

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1 These photographs are included to identify typical PWFDs. The deployment shown may not necessarily be appropriate or compliant.
The question for ANSBAP is whether PWFDs are suitable for this task. The paper does not consider the performance of PWFDs where installation or maintenance deviates from that specified by the manufacturer.

ANSBAP ASSESSMENT PROCESS

The assessment process is comprehensive, covering issues such as barrier performance, vehicle performance, occupant injury, effect on other vehicles and occupants, materials and manufacture, operation including deployment, repair and demolition, environment, worker health and safety over the whole of its deployment life and documentation issues.

The assessment process involves a risk-based evaluation performed by a panel of relevant discipline specialists. The aim of the evaluation is to determine the risk to stakeholders if a safety barrier product is impacted by an errant vehicle. The panel determines the risk by utilising an event tree approach to consider:

- a scenario – ‘what if an event occurs?’
- a consequence – ‘a level of damage (for example serious injury) that might occur to this target group?’
- issues – ‘what specific aspects of the product produce this consequence?’
- probability – ‘what probability can be assigned to the consequence as a result of the issues identified?’.

If a serious issue is identified, a product may be rejected, although generally any issues raised result in restrictions in its use in the design of the roadside and its installation.

In particular, the assessment seeks to establish key design parameters including point of need, i.e., the point at which a barrier system becomes an effective barrier, and whether the performance of the barrier is wholly independent of the terminal treatments. It also establishes whether or not the product is able to redirect vehicles.

ANSBAP provides a forum for reaching consensus on the properties of a barrier and for progression towards national consistency in both the types of barriers in use and in their design and deployment. An example of this and one that is relevant to this discussion on PWFDs is that ANSBAP has determined that a longitudinal safety barrier must have at least one terminal option available i.e. it must be deployable as a complete system.

Current guidance

Guidance on acceptable vehicle performance is available from both Australian and overseas standards.

In its scope, the current Australian Standard for road safety barrier systems AS/NZS 3845 (Standards Australia 1999) “…sets out the requirements for roadside devices that provide some degree of redirection and containment capability when impacted by a vehicle, or provide controlled absorption of the kinetic energy of a vehicle that is on a collision course with some significant obstacle”.

Neither redirection nor containment is further defined. However, mention is made of “become effective”.

AS/NZS 3845 requires inter alia that for any barrier system, there needs to be documentation on the performance of the barrier system based on a number of attributes and dimensions. AS/NZS 3845 Clause 2.3.5 (b) states:
The working width and the dynamic deflection width that applies to the road safety barrier system at the test level achieved. Where anchors are part of the road safety barrier system, the relationship between the anchorage spacing, the working width and the dynamic deflection width shall be specified. Where the road safety barrier system comprises inter-connected elements, then any relationship between the number of units, the working width and the dynamic deflection width shall be specified.

AS/NZS 3845 recognises that the performance will be based on the distance between the anchors and the number of units.

The Australian Standard continues, in Clause 2.3.5.(c) that the point where the system becomes effective and the minimum length needs to be identified. This information is required to enable engineers to appropriately design the field deployment of the barrier system such that it will offer ‘effective’ protection.

AS/NZS 3845 also requires that all road safety barrier systems shall be crash tested, and provides guidance on the testing protocol to be used for crash testing. The preface to the Standard states that “The National Cooperative Highway Research Program (NCHRP) of the United States Report Number 350 has been adopted as the basis of testing” (Standards Australia 1999).

Very broadly, NCHRP 350 (Ross et al. 1993) defines the U.S. requirements for testing and outcomes for barrier systems and end terminals. A range of ‘test levels’ are nominated and for each test level a suite of tests must be undertaken. For each test, the impacting vehicle is defined in terms of body shape, mass and centre of gravity, and the impact conditions are defined in terms of speed and impact angle.

Notably, AS/NZS 3845 includes a Test Level 0 (TL-0) that is not included within the NCHRP 350 testing protocol but was added “to the test Matrix with the intention of setting a minimum credential requirement for all plastic barriers at roadwork sites”. It replicates the TL-1 speed and angle requirements but substitutes a mid-size 1600C vehicle (1600 kg) for the 2000P vehicle (2000 kg pick up/utility vehicle).

Section 1.3 of NCHRP 350 describes the recommended generalised performance outcomes for a roadside safety feature. It states (after reformatting):

The safety goal is met when the feature either:

1. contains and redirects the vehicle away from a hazardous area
2. decelerates the vehicle to a stop over a relatively short distance
3. readily breaks away or fractures or yields
4. allows a controlled penetration
or is traversable without causing serious injuries to the vehicle’s occupants or to other motorists, pedestrians, or work zone personnel.

NCHRP 350 recognises that different roadside safety features will act in different ways and so different performance outcomes are required to be met. It allows a safety feature to meet its safety goal if any of the above performance outcomes are present, but it does not link the performance outcome to any particular device. The question for ANSBAP was to decide if any or all of these performance outcomes are applicable to a safety barrier, in particular whether a safety barrier should or must redirect.

NCHRP 350 does give further information that might provide guidance on the need for redirection including in its Glossary the definition of pocketing and its potential impact “If, on impact, a redrective device undergoes relatively large lateral displacements within a relatively short longitudinal distance, pocketing is said to have occurred. Depending on the degree, pocketing can cause large and unacceptable vehicular decelerations”. NCHRP 350 defines
“snagging” in a similar way to pocketing. It advises that “snagging might cause large and unacceptable vehicular accelerations”.

In Section 5.4, NCHRP 350 describes the evaluation characteristics of the post impact trajectory of the vehicle. It indicates that pocketing and snagging are undesirable and that the redirection should be smooth. It states:

… Criterion ‘L’ (which describes the maximum occupant impact velocity and ridedown accelerations) is included to limit pocketing or snagging of the vehicle and the post-impact consequences of excessive pocketing or snagging, such as a high vehicular exit angle or spin-out of the vehicle. It is preferable that the vehicle be smoothly redirected (for redirective devices), and this is typically indicated when the exit angle is less than 60 percent of the impact angle. Acceptable post-impact behaviour may also be achieved if the vehicle is decelerated to a stop while vehicular-barrier contact is maintained, provided all other relevant criteria of Table 5.1 are satisfied.

NCHRP 350 and subsequent documents would appear to suggest that a good device is one that redirects whilst accepting that close to the end of the device it may gate.

However, a desire to open up access to all creditable products and a recognition that crash testing supplies data that is only the starting point for the ANSBAP assessment process has led the road authorities to consider other testing regimes such as the European Standard EN 1317 (European Committee for Standardization 2010). This has also been acknowledged in the current draft revision of AS/NZS 3845.

EN1317 uses an ‘exit box’ to define acceptable post impact vehicle trajectories. The vehicle is to leave the barrier system facing in a forward direction and it should be at a low angle to the barrier. The exit box has lateral width defined as a function of vehicle length and width. The exit box is created and virtually positioned when the last of the vehicle’s wheels recrosses the original line of the barrier. Thus to enter the exit box, all wheel tracks must be on the traffic side of the initial line of the barrier. The vehicle must then leave the box at a relative low angle. The exit box concept is shown in Figure 2 from the 2010 version of the CEN Standard EN1317-2.

To satisfy the exit box criteria, the device must be redirective.
“...The vehicle shall leave the safety barrier including vehicle parapet after impact so that the wheel track does not cross a line parallel to the initial traffic face of the system, at a distance A plus the width of the vehicle plus 16% of the length of the vehicle within a distance B from the last (namely closest to the downstream end of the barrier) point P, where the last of the vehicle wheel tracks re-crosses the original line of the traffic face of the barrier after initial impact...”

**Figure 2: Extract from EN1317-2:2010 depicting the ‘Exit Box’**

The current draft revision of AS/NZS3845 also recognises that the Manual for the Assessment of Safety Hardware (MASH) (AASHTO 2010) has superseded NCHRP 350 in the US. MASH defines both gating devices, pocketing and snagging in the same way that NCHRP 350 does. However, MASH also adopts the exit box concept from EN 1317, reinforcing the principle that a barrier should be redirective.

In addition to specifying requirements for vehicle trajectory and redirection, EN 1317 also recognises that the length of the test installation is critical. EN 1317-2 cl.5.3.2 includes:

> The length of the safety barrier ... tested shall be sufficient to demonstrate the full performance characteristic of any longer installation... The test lengths shall be defined.... so that the car test(s) demonstrates the maximum severity of impact, and the large vehicle test demonstrates the maximum dynamic deflection characteristics.

This approach is reiterated in NCHRP 350, section 2.3.2.1 of which states that:

> ...the length of the test section should be such that (1) terminals or end anchorage devices do not influence in an abnormal manner the dynamic behaviour of the barrier and (2) the ability of the barrier to contain and redirect the test vehicle in the recommended manner can be clearly ascertained.
The requirements of both NCHRP 350 and EN 1317 are clear in that testing of a safety barrier should not be influenced by the terminals or end anchorages.

Both issues raised in this section are pertinent especially in the context of a work zone where workers are likely to be behind a barrier system. A system that captures and directs a vehicle into a work zone rather than (as required by EN 1317 and desired under MASH) redirecting the vehicle away from the work zone is undesirable. And secondly a suite of testing which yields artificial results that may give a designer over-confidence about the deflection performance of a barrier system is also problematic. Both points are investigated further below.

OBSERVATIONS ON CRASH TEST PERFORMANCE

Initial observations

A number of PWFDs have been assessed by ANSBAP, and these have been considered concurrently in order that deliberations would be equitable.

During the initial review of the performance characteristics of the submitted PWFDs, a number of general observations were made:

- Deflections were large.
- Some PWFDs snagged all test vehicles.
- Some PWFDs snagged some test vehicles.

In one case where all vehicles were snagged, ANSBAP was informed by the supplier that ‘capture’ was the intended outcome of the system. Thus this behaviour can perhaps be designed into (or also out of) the performance of a PWFD.

This led to further examination of the circumstances around capture utilising those PWFDs that exhibited mixed behaviour i.e. those that captured some vehicles and redirected others. A ‘pattern’ of performance behaviours was emerging.

The panel observed that for PWFD products where mixed behaviour was present:

- Higher energy vehicle impacts result in either the nose of the vehicle ‘snagging’ in the system and rotating the vehicle, and/or the vehicle trying to punch through or climb over the system.
- Where capture occurred, the PWFD system moved a considerable distance (as much as 5-6 m) laterally into what would be the work zone.
- Redirection was more likely to occur at lower energy impacts.
- With some tests, the captured vehicles moved the test installation longitudinally: either the upstream end or both the upstream and downstream ends moved.

This led to the theory that a given PWFD system will perform differently depending on its structural design, the length of the installation and the energy of the impact and that there is a threshold value for energy below which a PWFD may be expected to redirect and above which it may be expected to capture.

In general:

- These systems gate at the ends.
- Where the length is below a critical value or the impact energy is above a threshold value then capture or snagging occurs.
• Redirection will only occur if the structural design of the PWFD system allows it and the length of installation is long enough.

Each of these behaviours will be explored below. Some of these observations are also applicable to other systems, but this will not be discussed in this paper.

**GATING**

Gating behaviour is observed at the end of a PWFD system and this mode of operation is not unexpected.

The ends of a PWFD are not attached to the pavement and rely on gravity for restraint. Flexibility is inbuilt into the system either through the jointing mechanism or the ‘crushability’ of the units themselves or both.

As above, and as depicted in Figure 3, the approach end of a string of PWFDs will invariably ‘gate’ on impact, meaning that the impacting vehicle passes behind the system.

![Figure 3: ‘Gating’](image)

The energy absorption on the nose is negligible. The length over which the PWFD will gate is a function of the structural design of the system. It might be anticipated that as the impact point moves further into the line of PWFDs, the energy absorption increases and at some point the behaviour will cease to be that of gating.

**CAPTURE AND ENERGY ABSORPTION**

As the impact point is moved further downstream from the head of the system, the ballast in the head of the system will reach a point where the PWFD string:

• cannot contain the vehicle and the result is penetration, overtopping or under riding
• contains and arrests the vehicle on the traffic side of the system
• contains and redirects the vehicle on the traffic side of the system.

The first of these modes is unacceptable.

The second of these modes has been described by ANSBAP as ‘capture’ and there are two sub-modes of capture observed. These are described immediately below.

The third mode, i.e. redirection, is described later.
Pocketing and total energy absorption

As the impact point moves further into the line of the PWFD (i.e., further downstream from the head of the system), the restraining mass increases sufficiently to prevent gating. This is illustrated in Figure 4. There is insufficient energy to gate the system.

![Figure 4: Vehicle is snagged](image)

However, the vehicle has enough energy to move the leading units and after it is snagged both the PWFD system and the vehicle move together. This is illustrated in Figure 5.

![Figure 5: Combined movement](image)

This will continue and lead to the complete dispersion of the impact energy. Figure 6 shows the outcome of a pocketing impact.
In these scenarios, there is a risk that the vehicle will penetrate the system. It will depend on the tensile strength of the connection between units and the integrity of the units themselves, typically including any steel skeleton in and on the device that will interact with the vehicle if the plastic shell has been destroyed.

In many of these cases, the vehicle's direction of travel does not change appreciably.

Notably, the further the impact point is from the end of the barrier so the number of barrier units that are moved is greater and the greater are the occupant decelerations and the Acceleration Severity Index (ASI) which includes the accelerations in the mutually perpendicular (lateral, longitudinal and vertical) directions.

**Snagging, yawing and partial energy absorption**

As the restraint provided by the PWFD units upstream of the impact point increases further, the vehicle energy will not be sufficient to ‘pocket’ but the interaction may still snag the vehicle. Whether this occurs is dependent on vehicle impact energy, the structural characteristics of the PWFD and any system restraint including its length.

There is still a tendency for the ends of the PWFD system to move longitudinally when impacted but to a lesser degree than in the full energy absorption sub-mode. There is also a tendency for the vehicle to move downstream along the face of the device.

Where restraint is significant, and at higher impact energies (higher speed, higher mass, and or higher impact angle), PWFDs are observed to demonstrate a tendency to snag the nose of a vehicle and rotate (or yaw) the vehicle into the system where the vehicle is not brought to a halt and typically leaves the PWFD in the reverse direction and this is depicted diagrammatically in Figure 7.
As the restraint exceeds the level required to trigger this second form of capture, the behaviour will asymptote to a stable result. This is explored later in the discussion about combined behaviours.

The more units that are moved, the greater are the occupant deceleration and ASI values. What is more of an issue is the tendency to yaw, which produces high lateral accelerations on the vehicle and a greater chance of head injuries as the occupants collide with the vehicle structure. Seat belts offer limited restraint against lateral accelerations.

Other capture observations

A common observation during crash testing is that the leading and trailing ends of the system typically move longitudinally during impact as depicted in Figure 8.
Figure 8: Longitudinal Movement

This occurs where the tested system length is insufficient to provide the restraint force necessary to induce the performance expected by a longer system. This implies that the system may behave differently if the PWFD string is either longer or shorter than the crash test configuration.

One significant concern is that high energy impacts into PWFDs are observed to be close to realising total breach of the system, which implies that there is little tolerance for an over-capacity impact. As such, there is a concern that a longer system with more ballast would not be so easy to displace longitudinally and so hence may be more prone to breach due to failure of the system. Conversely, a shorter system could be expected to have higher deflections, as movement of the whole system would be less impeded by the ballast provided by the upstream and downstream ends. The consequence is that there is no certain knowledge about minimum and maximum system lengths, and more importantly the expected behaviours for system strings of different lengths.

A further observation is that when pocketing occurs, the vehicle does not usually return to the traffic side of the original line of the device. When capture/yaw occurs the vehicle may not return to the traffic side of the original line of the system, or if it does, it will most likely not be in the forward direction. It is therefore unable to enter (and leave) the exit box and from this definition the system cannot be considered to be redirective.

REDIRECTION AND ENERGY LEVEL

If a PWFD is designed or has characteristics that make it ‘capture’ then it is unlikely to redirect.

However, most PWFDs have some ability to redirect an errant vehicle. This will be observed at lower impact energy levels energies (i.e., lower speed, lower mass and or lower impact angle). A redirective impact, for a PWFD, is depicted diagrammatically in Figure 9, although this is not precisely the same as other barrier types. Also depicted in Figure 9, is the ‘exit box’ concept from EN 1317. It reinforces the desirability of the barrier or device redirecting vehicles rather than capturing them.
Redirection is a desirable outcome. The benefits are typically:

- reduced energy absorption by the system and hence lower occupant injury
- reduced intrusion into the worksite and hence reduced interaction with workers
- more predictable and consistent outcome
- more effective management of energy as the system does not attenuate all of the errant vehicle’s energy.

The issue for ANSBAP was determining whether there was a limiting energy level and if so what it may be.
ANALYSIS OF CRASH TEST BEHAVIOUR

Redirective devices

In general, redirection becomes increasingly more difficult as the vehicle proceeds further over the initial longitudinal line of the PWFD system.

ANSBAP has observed that when PWFDs do redirect, the deflected shape is long and (relative to the deflected length) shallow, and not a short and deep bowl, which suggests that any lateral momentum/force is being effectively transferred to the upstream and downstream units. This emphasises the role of the structural design of the device on its performance. For instance, it might be that the joints in such a system are acting not as a pin and rotating, but as a 'fixed' joint and are NOT rotating. The point is that the more the device acts like a beam rather than a chain, the higher then the chance of redirection. To do that, the joints need to have high resistance to rotation, which then transfers the resistance to the integrity of the main frame structure in order to resist failure.

For temporary unanchored barriers, which rely on the friction of the units on the pavement or ground to resist the impact, the maximum lateral energy of the impact is related to the mass of the units and the number of units moved and how far they can be moved.

Figure 8 indicates an important characteristic of a PWFD. Even when they are able to redirect vehicles, they have a tendency to continue to deflect further beyond the line of trajectory of the vehicle. Once the units are moving they continue to travel some distance into the work zone. This has two implications. The first is that this creates larger deflections than other barrier types (which stop moving more quickly), and this must be allowed for in a work zone design. Secondly, these short and deep bowls would make the device especially ineffective for another impact. Both of these characteristics are undesirable.

The closest point to the anchor where a barrier system is effective is termed the 'point of need'. Typically the ANSBAP uses the information in full-scale tests to establish the point of need.

A designer describing the installation details for a barrier, including temporary barriers needs to account for the likely movement of the barrier on impact. This is not just the likely movement during a controlled compliance test but rather under expected impacts with the field installation. If the barrier system is redirective and the impact is between upstream and downstream points of need, then the designer can be confident that the system will perform in a similar fashion to the full-scale compliance testing. Diagrammatically, the deflection will decrease as the impact point moves further from the end of the barrier (Figure 10). The deflection of a gating system is artificial as the vehicle is allowed to proceed beyond the 'deflected' barrier. Accordingly, it is a requirement that the barrier is appropriately extended upstream of the worksite.

It is also important to consider the likely crash severity for the occupants of the impacting vehicle. The ASI values provide a convenient overview parameter. Figure 10 shows the likely PWFD system deflection and ASI values for impacts at different locations along a 'redirective' system. Note that there is uncertainty about the device’s performance in the transition zone before the point-of-need (PON). It is also noted that the transition zone may be quite short.
Capturing devices

The performance of ‘capturing’ devices is even more uncertain. It is expected that the performance will be as depicted in Figure 11.

Deflection will decrease as the impact point moves further from the end in a similar fashion to a redirective device (although the distances will not be the same).

The ASI plot for a ‘capture’ device is expected to be quite different to a ‘redirective’ device. A capture device will attenuate all the energy of the errant vehicle. A redirective device only attenuates some of the energy and causes the vehicle to continue sliding along the system or moving away from it.

For capture devices, the ASI for an impact is likely to increase as the impact point is moved downstream simply because vehicles are arrested in shorter distances. Smaller deflections will occur because there is a greater mass of units upstream and downstream of the impacting point and these apply a larger restraining force on the units in the impact zone. Also as impact moves further downstream, the sub mode of capturing changes from pocketing and total energy attenuation to snagging, yawing and partial energy attenuation. The result is a decrease in the acceleration in the longitudinal direction but with an increased propensity for yawing, there will be higher lateral deceleration levels. The precise ASI relationship for a device is expected to be even less well defined. It might reduce a little, increase a little, or remain much the same. In any case, based on the available test data, it is indeterminate.

Figure 10: Effect of impact point on the performance of ‘redirective’ PWFDs
Without extensive testing on long installation lengths, where there is more longitudinal restraint on the PWFD system, the ANSBAP is concerned that the connection between the units might fail and allow the vehicle to breach the device.

Figure 11: Effect of impact point on the performance of ‘capturing’ PWFDs

The outcomes of an impact with a capture device depend on the vehicle type, impact speed and angle, the location of the impact point with respect to the end of the installation, and the overall length of the installation. Capturing devices are likely to have larger deflections than redirective devices. The performance is considerably more difficult to predict than for a redirective device.

Without significantly more information from full-scale impact testing, ANSBAP cannot responsibly quantify the performance of such devices for use on Australian roads.

At what energy level can PWFDs redirect vehicles?

PWFDs will redirect vehicles if the lateral kinetic energy (or impact severity) is low. Just how low was a question ANSBAP wanted to answer. Essentially the panel used a range of tests to establish when they considered that vehicles were redirected.

On a number of occasions, the limiting value of the impact severity was determined to be in the order of 40 kJ. Whilst one product appeared to provide a redirective outcome at a higher value, it is arguable that the limiting energy level is not product independent and that ultimately, the value depends on the design of the device. It may also be that for that test the vehicle and device interaction was optimised.
A simple model for the analysis of PWFD operation can be developed by looking at the lateral energy of the impact and the distance the units must move in order that the lateral energy is attenuated. It is recognised that energy is not a vector, as is velocity, but the use of the lateral kinetic energy is applicable in analyses of this type.

The following assumptions are made:

1. The interaction occurs over 20 to 35 m depending on the impact speed.
2. The mass of the PWFD is 300 kg/m.
3. The coefficient of friction between the device and the pavement is 0.6.
4. The impacting vehicle has a mass of 2000 kg.

As an example, if the impacting vehicle is travelling at 70 km/h with an impact angle of 25° and if the vehicle is assumed to travel 25 m along the PWFD system then:

a. The lateral kinetic energy is 67.5 kJ.
b. The total mass of the units moved is 7500 kg.
c. Assuming that all units are moved the same distance, the force required is 44.4 kN and the units are moved an average distance of 1.5 m.
d. The path taken by the vehicle approximates to a parabola and as a consequence the maximum distance travelled is approximately 1.5 times the average distance the vehicle travels from the road.
e. Under the conditions described here the maximum lateral distance travelled by the vehicle is 2.3 m.

A full-scale test on one device under these conditions produced the same lateral movement of the vehicle, i.e., 2.3 m.

As stated in previous discussion above, the units will continue to move further than the vehicle due to their momentum. While it is not necessary to include this aspect in this calculation, in the same full-scale test, the device deflected 4.0 m.

If this analysis is repeated for speeds between 50 and 100 km/h and for impact angles between 5 and 25° then the results are shown in Figure 12. An envelope for the maximum vehicle deflections (occurs for the limiting impact angle of 25°), is also shown.

Figure 12 also includes the device deflection results from a number of other PWFDs where the performance was considered to be redirective. In only one test result were both the vehicle and device deflections both stated. This actual test result and the other redirective test results when compared to the envelope, show the device deflections are greater than the maximum lateral distance travelled by the vehicle.

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2 Devices with external fitments, such as W-beam rail, designed to improve barrier performance are not included in this analysis.
Lateral kinetic energies of approximately 40 kJ result in average lateral distance travelled by the vehicle of between 1.0 and 1.7 m. As 2000 kg vehicles are approximately 1.9 m wide, a displacement in this range should mean that some part of the vehicle remains on the traffic side of the initial line of the system so improving its probability of being redirected. At higher lateral kinetic energies, the calculated deflections are large and it is unlikely that vehicles will be redirected.  

Notably, the number of such redirective outcomes is quite low given the number of devices and tests submitted to the ANSBAP and illustrates forcibly the difficulty in getting PWFDs to redirect.  

For practical purposes, the ANSBAP considers that for a PWFD system to be redirective a general limiting lateral energy is 40 kJ. This approximates to an impact condition comprising a 2000 kg vehicle travelling at 50 km/h with an impact angle of 25°.  

The method used to predict deflection here is not dissimilar to the model proposed in Jiang et al. (2002). However accordant with that research, which notably focussed on collisions where the lateral energy did not exceed 40 kJ, it is argued that the method must be restricted to a crash outcome that results in a relatively symmetrical parabolic or circular bowl of deflection, where the vehicle does not pocket or tear the barrier. The observations described in this paper are that more severe conditions than those observed by Jiang (and generally exceeding 40 kJ) generally do result in an outcome which involves pocketing and/or tearing of the barrier, and as such the models cannot be used as reliable predictors for deflections at higher lateral energies in all test conditions.

**OBSERVATIONS ON CRASH TEST REPORTS**

ANSBAP critically reviews crash test performance as one part of its assessment. One of the concerning observations made by ANSBAP in reviewing the performance of PWFDs is that some crash tests certified by the testing agency as meeting the test regime evaluation criteria appeared to be not so. Some of the evaluation criteria deemed acceptable by the testing agencies but considered to be otherwise by ANSBAP were:
• The test article should contain and redirect the vehicle or bring the vehicle to a controlled stop. At least one test video showed the vehicle yawing and pushing the line of plastic units a considerable distance into a potential work zone.

• The vehicle should not penetrate, under ride or override the installation. At least one test video showed the vehicle straddling (overriding) the system.

• The vehicle should remain upright during and after collision. At least one test video showed the vehicle rolling an extreme amount, before stabilising, indicating that, in field conditions, there could be a high likelihood of the vehicle overturning.

This may be the result of a difference in interpretation. These observations underline the need for rigour in the assessment process that ANSBAP undertakes.

COMPARISON WITH OTHER TEMPORARY BARRIERS

In looking critically at the use of PWFDs in the work zone, it is useful to compare them with performance of other temporary barriers:

• There are a number of portable concrete barriers available, that have test deflections in the range of 0 to 1.5 m and are observed to redirect an impacting vehicle across a range of impacts from near to the nose of the system. In addition, concrete (unlike PWFDs) can be attached to a crash cushion making it redirective from the nose. Some of these systems can be anchored at the ends (unlike PWFDs) and can achieve impact load capacities significantly beyond those of PWFDs.

• There are a number of steel barriers available that, as free-standing units, have test deflections larger than are observed for concrete barriers, in the range of 1 to 4 m, but which is generally lower than that of PWFDs. Once their development length is achieved, they usually redirect the impacting vehicle. These barriers (unlike PWFDs) can be attached to crash cushions and/or pinned, and the deflections are then reduced to very low values, for example, 0.3 m. Some of these systems can be anchored at the ends (unlike PWFDs) and can achieve capacities significantly beyond those of PWFDs.

The only advantage that PWFDs appear to have over other temporary barrier systems is their portability.

WORK ZONE LEGISLATION AND STANDARD

Work health and safety legislation

Australia has, for a number of years now, been moving toward national work health and safety legislation. A ‘model’ was developed and individual states are now putting the model into legislation. Examples are the Work Health and Safety Act 2011 (Queensland 2011) and the Work Health and Safety Act No 10 (New South Wales 2011), both of which came into force on 1 January 2012.

Of particular interest to those designing safety barrier installations is the requirement for ‘designers’ to take responsibility for the outcomes of any installation.

Both of the above Acts, at Section 22 require in part that:

‘The designer must ensure, so far as is reasonably practicable, that the plant, substance or structure is designed to be without risks to the health and safety of persons—.......

and follows this with a list of activities that includes:
(a) who, at a workplace, use the plant, substance or structure for a purpose for which it was designed......

These Acts say that Section 22:

applies to a person (the designer) .....that designs ....... (c) a structure that is to be used ........as, or at, a workplace.........

ANSBAP considers work health and safety in its assessment and considers that designers should be made aware of the performance issues associated with the specification and use of PWFDs.

**Australian Standard AS 1742**

AS 1742 Part 3 (Standards Australia 2009) describes requirements for the deployment of barriers including:

Road safety barrier systems are designed to provide a physical barrier between the travelled way and the work area, which will inhibit penetration by an out-of-control vehicle ... and will have vehicle redirecting properties.

This reinforces the ANSBAP view that barriers are to be redirective.

AS 1742 Part 3 also requires that a ‘containment fence’ be placed on the limit of the dynamic deflection for a work zone barrier. Whilst its primary use is to keep workers out of the deflection zone, it is also intended to keep that deflection zone clear of materials, equipment and plant in order that the barrier may be allowed to deflect without impediment and thus perform its role of vehicular redirection.

Many, if not most, work zones in Australia involve working in close proximity to passing traffic. These work zones are generally limited in terms of ‘free’ space between the work zone and the passing traffic and hence the requirement for a containment fence to sterilise this free space emphasises the need for lower deflection barriers.

![Diagram of protective fencing behind a safety barrier system](image)

**FIGURE 3.5 PROTECTIVE FENCING BEHIND A SAFETY BARRIER SYSTEM**

*Figure 13: Extract from AS 1742.3 (European Committee for Standardization 2010) showing the ‘containment fence’ concept*

To comply with the notions in AS 1742.3, a PWFD thus has to be restricted to an impact severity that will ensure that the deflections can be accommodated within the space available. As stated previously, practically the area for device deflection is severely restricted. Unacceptably high deflections are observed to occur at impact energies above 40 kJ.
DESIGN AND IMPLICATIONS FOR TESTING

For the purposes of design of a safety barrier at a work zone, it is necessary to have confidence in the knowledge about how a proposed installation is expected to behave:

- for the workers, so that incursion into the work zone is avoided
- for the occupants of the errant vehicle, so that the degree of deceleration can be determined.

Designers of work zones should select a barrier with due consideration of fitness for purpose i.e., primarily containment capacity and deflection.

It is usually the administrating road authority that determines whether or not a barrier system may be used, and such, in response to the second dot point above, a determination is based on results derived from crash testing which takes occupant severity into account. Certainly ANSBAAP considers impact decelerations and occupant severity during its product assessment.

Whilst PWFDs generally exhibit acceptable deceleration outcomes, the consequence is that deflections are larger than for other device types. Thus, for PWFDs, design ultimately looks at deflection i.e., can the deflection be accommodated within the available area?

As observed previously, the deflection for a PWFD depends on the performance characteristics of each device which, as discussed previously, are partly dependent on both distance from the terminal to the impact point and on the length of the installed system, and partly a function of the manufacture, size and shape of the units and their connections.

At the head of a system, PWFDs gate at the nose. In theory, gating is an acceptable form of crash mitigation, as long as the behaviour of the PWFD and impacting vehicle is predictable and can be accommodated by the roadside. After the device has gated, the impacting vehicle should not collide with other hazards, or workers. However, for most work zones, the provision of large run-out areas is not practical.

It is also necessary to have confidence in knowing where the transition between gating and the subsequent form of operation occurs. Designers of work zones especially need to know where gating ends as well as the extents of other modes of operation in order to be able to manage a work zone such that the area likely to be encroached by an errant vehicle is maintained free of personnel, plant and materials. This information i.e., the transition between gating and subsequent form of operation may not be at the junction of the terminal and the longitudinal device. For PFWDs information about where this occurs is not readily available or complete. This uncertainty is often compounded because testing is undertaken on test lengths which move longitudinally during impact.

Whilst the decelerations (ASI) in this subsequent zone might still be relatively low, the issue remains that there is often insufficient information to undertake confident design.

Where capture is the subsequent ‘stable state’ form of operation for the longitudinal system (i.e., the same capture outcome occurs regardless of length), it is necessary that designers know, for the purposes of allowing for deflection, where the transition between the first and second sub modes of capture occurs. Since this relationship is generally undetermined, it may not be possible to design a system for a given work zone.

Additionally, where capture is the stable state mode of operation there is a zone of uncertainty between gating and capture where occupant severity levels are expected to be higher than are measured during the normal testing regime, and possibly longitudinal tension in the system may peak. Not knowing this information may be a challenge for road authorities.

Only where the stable state mode of operation is redirection will designers be confident of system deflections, and this has been shown to have quantifiable lateral energy threshold, typically (but not absolutely) around 40 kJ. However, as previously stated if the system has
moved longitudinally during testing, the capacity of the system and the deflections measured are questionable.

Thus, the uncertainty in all of the above promotes the notion that PWFDs need to be tested more extensively, i.e., beyond the generally accepted minimum, otherwise key parameters for designers such as deflection, length of effective system, and hence point of need remain indeterminate.

**SUMMARY**

- Plastic Water-Filled Devices (PWFDs) are required to redirect to be classified as safety barriers.
- PWFDs (even if redirective, but more so if not) have different modes of performance over their length.
- PWFDs typically change their mode of operation from redirection to capture when the lateral impact energy exceeds ~40 kJ.
- PWFD performance is difficult to predict and therefore it requires significantly more testing than other barrier types to clarify expected outcomes for designers.
- Test regimes for PWFDs should include sufficient testing in order to identify the various change points in their modes of operation.
- Test regimes for PWFDs should include sufficient testing in order to identify maximum occupant injury and where it occurs.
- PWFDs should be tested using sufficient test lengths in order that the test is independent of the length i.e., that the ends do not moving either longitudinally or laterally and thus the capacity of the device is adequately tested.
- Designers and road authorities need to be aware that there is an increased risk of adverse performance as the energy level increases, that redirection is less likely after 40 kJ, and that this approximates to an NCHRP 350 Test Level 1 (TL-1) impact condition (i.e., 50 km/h, 25 degrees, 2000 kg).
- In representing the community and exercising responsibilities under WHS legislation, the authors expect that PWFDs will henceforth be used more informatively e.g., for short term works where their ready deployment can be used to advantage.

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