Gap Analysis of Rolling Stock Crashworthiness Standards
Gap analysis of crashworthiness standards

**Synopsis:**
Rolling stock crashworthiness is regarded as a safety issue – but it also affects the society, environment and economy - the ‘triple bottom-line’. The Australian standard, similar to the USA and European standards has prescriptive provisions for rolling stock crashworthiness. In Australia, the crashworthiness of locomotives, passenger cars and freight wagons is prescribed largely using static loading, whilst the European standard permits simulation and dynamic modelling. Australian anti-climbing device is required to be designed for static energy. Crash energy management (or absorption) devices in lighter locomotives can be problematic. Level crossing crash scenarios due to operation of heavier, faster, longer road trains in Australia are unique and require in-depth consideration.

**REVISION/CHECKING HISTORY**

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<td>1</td>
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Gap analysis of crashworthiness standards

Executive Summary

Rolling stock crashworthiness is regarded as a safety issue – but it also affects the society, the environment and the economy - the ‘triple bottom-line’. For example, non-crashworthy container wagons carrying chemicals can represent large scale environmental hazards and at times nearby towns require evacuation – leading to enormous social issues. Such rolling stock can also cause significant damage to the track infrastructure if involved in derailment - which can potentially close down train lines, leading to loss of revenue. Crashworthiness standards aim at minimising the severity of the crash events thereby saving lives, the environment, and the track infrastructure. This report compares the Australian Rolling Stock Crashworthiness Standards with comparable European and US standards.

As crashworthiness standards are based on historical accident statistics, a summary of Australian rail accidents from the engineering characteristics of the trains is also included in this report. Crashworthiness is also affected by the operating environment and vehicle classifications. Conformity to a standard is based on permissible stress in the body structure, bio-mechanics principles for passengers’ survivability and remaining volume available in survival areas.

The analysis of Australian major rail accident data has revealed that the lateral impact scenario at level crossings is unique due to the operation of heavier and longer road vehicles (relative to international standard) at 90km/h. More head-on collisions occurred at an operating speed of 10km/h and 90km/h – which is higher than the European statistics. On average, impacts on the body structure involved a total kinetic energy of 220MJ.

While the US and European design standard refers to vehicles by their functions (passenger/freight), the corresponding performance standards categorise vehicles by their operating environment. In spite of the unique operating environment in Australia, the Australian standards do not classify crashworthiness as per the operating speed – perhaps the speeds are well under the Tier-1 (USA) 200km/h limit.

The US relies on self-certification; therefore, heavier static loading and rigorous testing are central to their standard. The European standard is less prescriptive where modelling and optimisation of design are encouraged.

In Australia, heavy locomotive loadings are currently twice or three times that of passenger vehicles. As a result, it may be difficult to meet energy absorption requirements on light locomotives. The Australian standard has provision for anti-climb devices, the design of which is based on static rigidity. However, the European approach is to test dynamically.

The Australian standards allow shaped corner posts and collision posts to comply with the overall line of the vehicle. The impact from a US scenario with a proxy can lead to climbing of the proxy with variable results amongst vehicles of different shapes. It is particularly problematic for full-size testing considering the cost of a single test.
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Abbreviations and Acronyms

No Special Symbols

AAR – Association of American Railroads
APTA – American Public Transit Association
ATSB – Australian Transport Safety Bureau
FRA – Federal Railroad Administration
RISSB – Rail Industry Safety and Standards Board
RSA – Railway Safety Act
TGV – Train à grande vitesse (high-speed train)
TSBC – Transportation Safety Board of Canada
1. Introduction

This report presents similarities and differences in rolling stock crashworthiness standards – from Australia and some selected overseas countries. The assessment of differences is referred to as a gap analysis. This document provides qualitative comparisons between the presented standards by focusing on Australian railway conditions. This document does not give (and does not attempt to give) indications regarding the performance or rating of the standards. Tables and figures present general cases - specific requirements and exceptions can be found in the original standards.

Crashworthiness standards are based on historical evolution of the railway industry and accident statistics, as well as on environment and vehicle classifications from which crashworthiness scenarios...
are derived. Conformity to a standard is based on permissible stress in the body structure, biomechanics principles for passengers’ survivability and remaining volume available in survival areas.

In Australia, the Rail Industry Safety and Standards Board (RISSB) is developing a new set of standards called the AS75## series. In particular, section AS7520 parts 1 to 4 (see RISSB 2008, Pt1, RISSB 2008, Pt2, RISSB 2008, Pt3 and RISSB 2008, Pt4) are drafts aimed at providing national specifications for both design standards and performance standards. Parts 1, 2, 3 and 4 respectively describe locomotives, freight vehicles, passenger vehicles and maintenance vehicles. The CRC for Rail Innovation project R3.114 aims at analysing standards applied overseas, establishing statistics on Australian railroad accidents and studying the applicability and limits of crashworthiness standards under local conditions. This report focuses on overseas standards and compares them to AS7520 parts 1-4.

![Figure 2: Parameters for Gap analysis](image-url)
A literature review of international standards highlighted a set of current overseas practices from Europe, Canada and the United States of America.

In Europe, a four-year project on crashworthiness (SAFETRAIN) was carried out in 1997. It improved railway passenger safety through the development of crash energy management technologies, assessment methods and criteria. The outcome of these research activities was the basis for the EN12663 design standard (European Committee for Standardisation 2000) and the EN15227 performance standard (European Committee for Standardisation 2008). These standards have been in operation since 2001 and 2008 respectively in the member countries of the European Union.

In the United States of America, the Federal Railroad Administration (FRA) defines minimum and mandatory structural and safety requirements nationwide. The 49CFR238 standard (FRA 1997), along with its January 2010 update (FRA 2010) as well as the 49CFR229 (FRA 1997) provide crashworthiness requirements and design testing for passenger vehicles and locomotives. In addition to the FRA, the American Public Transit Association (APTA) gives a set of recommendations to the railway industry. The latest update is the APTA SS-C&S-034-99 Rev2 (APTA 2006). While the recommendations from APTA are not mandatory, they are considered as best practice and widely accepted in the USA. APTA and FRA collaborate to define standards; the SS-C&S-034-99 standard was based on 49CFR238 and 49CFR229. The January 2010 update of 49CFR238 included developments proposed in SS-C&S-034-99. A third organisation, the Association of American Railroads (AAR), develops recommendations on the American territories. It is a trade organisation that publishes a *Manual of Standards and Recommended Practices* for Canada, the United States and Mexico. In particular, S-580 - Locomotive crashworthiness requirements- provides minimum structural requirements for locomotives.

No crashworthiness standards for the railway industry were found for Canada. According to the Ministry of Transportation of British Columbia (Transport Canada 2010a), “the Canadian rail system includes both the federal and the provincial railways. Railways that cross provincial boundaries are governed by the federal legislation, while railways that operate strictly within the boundaries of the province are governed by provincial legislation”. Safety is ruled by the Federal Railway Safety Act (RSA), the latter is available on the Transport Canada website (Transport Canada 2010b). Information on this website is stated as “official” from June 2009. However, the RSA does not mention crashworthiness rules. In the document R99W0231 (TSBC 2008), the Canadian Transport Safety Board has reviewed an accident
involving freight trains that occurred in November 1999. The document explains that “Standards for crashworthiness of locomotives used in North American Railways are contained in the AAR standard S-580”. This suggests that Canada follows recommendations from the AAR S-580 for locomotives.

Other countries such as Japan and Russia were investigated but language barriers make the search of documents and their reviews impractical.

Europe and the US are different in numerous points regarding crashworthiness and follow different philosophies. Some of these differences have been analysed previously in the case of level crossing scenarios and published in Llana 2009. The gap analysis emphasises the differences between the two continents. The gaps are represented by arrows in Figure 1 and are ordered in a flow chart in Figure 2.

The analysis considers two aspects of the standards. The first aspect relates to classifications. It presents the context of applicability such as the type of vehicle, the environment of scenarios, etc. It is related to the evolution of the railway technologies, political decisions and accident records in a country. In this report, classifications are of three types: (1) accident classifications, (2) vehicle classifications and (3) scenario classifications. The second part of a standard refers to the process and methods used to scientifically ensure passenger safety. Two attributes are considered here: design assessment and performance assessment.
2. Classifications

2.1. Accidents

An extraction of data from the Australian Transport Safety Bureau (ATSB) accident reports over the period 1997-2010 was carried out. Because of the low occurrence of events, results were provided in the form of histograms such that the non-statistical significance of the results remains visible. Several engineering aspects of the data were presented in the figures and as areas for comment included:

1. The characteristics of the consists and obstacles in term of length and weight
2. The characteristics of the events in term of the velocity and kinetic energy involved
3. The characteristics of the impacts in term of orientation and their relations to the other characteristics above.

From the analysis, the following observations have emerged:

1. Freight and passenger trains have distinct signatures. There are commonly two peaks, one showing short and light trains (passenger trains) and the other showing longer and heavier trains (freight trains).
2. Trains were more often involved in collisions (62%) than derailments (38%).
3. The average velocity during derailments is higher than in collisions. In addition, derailments more often occur with freight trains than passenger trains.
4. The velocity of trains at collision exhibits peaks at 10km/h and 90km/h. On average, collision speeds at level crossings are within the bounds of the European scenario. However head-on collisions are higher than the EN15227 standard.
5. The kinetic energy involved in events was found to be less than 212MJ in 62% of the cases. The majority of these were less than 40MJ.
6. On average, impacts between 0° and 45° on the structure involved a total kinetic energy of 220MJ.
7. Impact angles from 0° to 45° are the most common and thus lead to a greater number of injuries and fatalities.
8. The ratio of injuries and fatalities at a given impact angle to the number of collisions at this angle shows that there may be more risk in impacts at 45° than at 0°.
9. The level of detail provided by the ATSB was an important factor in extracting the data set. Recent ATSB reports provide less detail on events. This may be an issue in capitalising and
expanding a crashworthiness culture in Australia.

2.2. Vehicles

2.2.1. Overview

The Australian standard provides four parts of relevance, namely 7520.1 (RISSB 2008, Pt1), 7520.2 (RISSB 2008, Pt2) 7520.3 (RISSB 2008, Pt3) and 7520.4 (RISSB 2008, Pt4) - each part with a focus on a particular type of vehicle, synthesised in Table 1.

Table 1: AU - Vehicle classification for design and performance standards

<table>
<thead>
<tr>
<th>Category</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotive vehicles</td>
<td></td>
</tr>
<tr>
<td>Heavy duty</td>
<td>Freight, heavy haul, interchange</td>
</tr>
<tr>
<td>Medium duty</td>
<td>Branchline</td>
</tr>
<tr>
<td>Light duty</td>
<td>Loco-hauled passenger operations, light duty freight</td>
</tr>
</tbody>
</table>
| Freight vehicles                  | Consistent with heavy duty category defined for locomotives | Coal/Steel wagons, ...
| Passenger vehicles                | Vehicles in which passengers are fare-paying customers | Commuting /interstate passenger trains |
| Infrastructure maintenance vehicles| -                                           | Track machines, road-rail vehicles |

The classification is based on vehicle function and capabilities. It does not identify environmental conditions apart from a supplementary note stating: “The requirements quoted in this standard are
consistent with general metropolitan and long distance operations”. The documents do not distinguish railways with or without level crossings, closed or open traffic, suburban or underground operations.

As of 2011, Australia does not make use of any high-speed rail (200km/h or above). The fastest passenger trains in operation travel at less than 160km/h. Such units are operated by Queensland Rail (Tilt Train) and Transwa (Prospector). Even though they are capable of travelling at speeds up to 210km/h, environmental conditions such as track capability limit their speed to 160km/h. All high-speed train projects have been denied since the 1980s (high-speed link between Sydney, Canberra and Melbourne).

**European standards** have two classifications – one each for design and performance as in Tables 2 and 3 respectively.

Table 2: EU - Vehicle classification for design standards

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freight</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Vehicles which can be shunted without restriction</td>
</tr>
<tr>
<td>P</td>
<td>Coaches and locomotives</td>
</tr>
<tr>
<td></td>
<td>Fixed units</td>
</tr>
<tr>
<td></td>
<td>Underground and rapid transit vehicles</td>
</tr>
</tbody>
</table>

The documents do not distinguish railways with or without level crossings, closed or open traffic, suburban or underground operations.
### Table 3: EU - Vehicle classification for performance standards

<table>
<thead>
<tr>
<th>Category</th>
<th>Definition</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C-I</strong></td>
<td>Vehicles designed to operate on TEN routes, international, national and regional networks (which have level crossings)</td>
<td>Locomotive, coaches and fixed train units (relates to P-I &amp; P-II from Table 2)</td>
</tr>
<tr>
<td><strong>C-II</strong></td>
<td>Urban vehicles designed to operate only on a dedicated railway infrastructure with no interface with road traffic</td>
<td>Metro vehicles (relates to P-III from Table 2)</td>
</tr>
<tr>
<td><strong>C-III</strong></td>
<td>Light rail vehicles designed to operate only on a dedicated railway infrastructure with no interface with road traffic</td>
<td>Tram trains, peri-urban tram (relates to some P-IV from Table 2)</td>
</tr>
<tr>
<td><strong>C-IV</strong></td>
<td>Light rail vehicles designed to operate on dedicated urban networks interfacing with road traffic</td>
<td>Tramway vehicles (relates to P-V vehicles from Table 2)</td>
</tr>
</tbody>
</table>

The design classification is given in European Committee for Standardisation 2000. It separates freight vehicles from passenger vehicles and locomotives - see Table 2. The classification is based on vehicle capabilities and functions, focusing on the structural strength of the vehicle in normal conditions. Design standards do not consider operational conditions such as the presence of level crossings. The second
classification is defined for performance standards in European Committee for Standardisation 2008. It applies to new designs of locomotives and passenger-carrying rolling stock. The European performance standard does not consider freight vehicles (category F-I and F-II) (European Committee for Standardisation 2000).

While the design standard refers to vehicles by their functions, the performance standard categorises vehicles by environment. This is found to be appropriate to define realistic crashworthiness scenarios since critical events are related to railway conditions and operation velocities. Table 3 summarises the classification. The European documents do not distinguish high-speed trains from standard trains. The track conditions implicitly suggest that crash events would not occur at high speeds. As an example, high-speed portions of French (TGV) railways are fenced and isolated from oncoming traffic by design. Even though a high-speed train can be categorised as a C-I, crashworthiness requirements will be confined to much lower velocities.

In the US, the 49CFR238 standard (FRA 1997) classifies the operating environment first. It includes railways operating intercity or commuter passenger train services connected to or part of the general rail system of transportation as well as railways providing commuter or other short-haul rail passenger train services in a metropolitan or suburban area. The standard rules out rapid transit operations not connected to the general railway system of transportation (such as subways). A sub-classification based on the speed of a service is given: Tier-I defines units operating at speeds not exceeding 200km/h while Tier-II relates to vehicles operating at speeds over 200km/h but not exceeding 240km/h. For each class, another classification exists based on the function or specificities of the vehicle such as locomotives, MU cars, cab-cars.

Table 4: US - Vehicle classification

<table>
<thead>
<tr>
<th>Categories</th>
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</thead>
<tbody>
<tr>
<td>Car body structure without CEM</td>
</tr>
<tr>
<td>Car body structure with CEM</td>
</tr>
<tr>
<td>Non-passenger-carrying</td>
</tr>
<tr>
<td>locomotives</td>
</tr>
</tbody>
</table>
The 49CFR229 standard (FRA 1997) includes locomotives that are not part of 49CFR238 [4] such as locomotives used for freight operations. There is no direct reference to a vehicle classification in the APTA document (APTA 2006), however the structure of the document shows a classification based on vehicle architecture with specific load applied on each category. This classification is effective for static loading and very detailed for the application of static forces on collision/corner posts. Table 4 provides a classification of trains in the US based on the analysis of the standards.
2.2.2. Analysis

Table 1 for Australia, Tables 2 and 3 for the European Union and Table 4 for the US summarise vehicle classifications in each country or union based on the relevant standards. All standards provide a vehicle classification. Each vehicle belonging to a class must comply with general requirements as well as specific requirements when applicable.

**High-speed vehicles:** Only US standards provide a category for high-speed vehicles. European standards have requirements on high speed lines in regard to incoming traffic such as the provision of fences and no level crossings, making a high speed collision scenario unnecessary. Australia does not currently operate any high-speed trains and no high-speed train projects are foreseen in the near future; there is no need to categorise high-speed trains or develop high-speed train crashworthiness scenarios in Australia.

**Environment:** As opposed to the European and US standards, the Australian standard does not provide any indication on the environment of a service even though the operating conditions of a line are strongly correlated with the type of accident. Crashworthiness scenarios should reflect this aspect in order to properly consider real dangers and avoid unnecessary design constraints on consists not being subject to such hazards. It is suggested that the development of Australian crashworthiness scenarios be preceded by an environmental and operational conditions classification.

2.3. Scenarios

2.3.1. Overview

The Australian design standard's requirements are referred to as proof loads.

Table 5: AU - Crashworthiness scenarios

<table>
<thead>
<tr>
<th>Locomotives and passenger vehicles</th>
<th>Freight vehicles</th>
<th>Rail work vehicles</th>
</tr>
</thead>
<tbody>
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<td></td>
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</tbody>
</table>

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Like-like collision head on: Stationary single test vehicle placed between two racks of 3 50t vehicle with one rack used as a buffer. Velocity is applied starting at 10km/h by 3km/h increments until a coupler force of 5500kN or a maximum of 20 km/h is reached.

Collision with a freight train fitted with buffer: Not applicable.

Collision at level-crossing: These consider longitudinal, vertical and combined loadings. The design scenarios are related to US standards, especially for locomotives and tend to follow more European specifications for passenger vehicles. Design standards and analysis are presented in more details in chapter 3.1 of this document.

Table 6: EU - Collision scenarios and collision obstacles

<table>
<thead>
<tr>
<th>Collision partner and conditions</th>
<th>Collision speed [km/h]</th>
<th>Identical train unit</th>
<th>See 4.2.3</th>
<th>See 4.2.3</th>
<th>See 4.2.3</th>
<th>The corner obstacle for tram collisions is defined in Figure C.7 of RISSB 2008, Pt1</th>
<th>See also 6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-IV</td>
<td>15</td>
<td>n.a</td>
<td>n.a</td>
<td>n.a</td>
<td>25</td>
<td>n.a</td>
</tr>
<tr>
<td></td>
<td>C-III</td>
<td>25</td>
<td>25</td>
<td>10</td>
<td>25</td>
<td>n.a</td>
<td>See table #</td>
</tr>
<tr>
<td></td>
<td>C-II</td>
<td>25</td>
<td>n.a</td>
<td>n.a</td>
<td>n.a</td>
<td>n.a</td>
<td>n.a</td>
</tr>
<tr>
<td></td>
<td>C-I</td>
<td>36</td>
<td>36</td>
<td>n.a</td>
<td>Vlc-50&lt;110</td>
<td>n.a</td>
<td>See table #</td>
</tr>
</tbody>
</table>
Operational characteristics of requirements

<table>
<thead>
<tr>
<th>Operational characteristics of requirements</th>
<th>All systems</th>
<th>Mixed traffic with vehicles equipped with side buffers</th>
<th>Mixed traffic with vehicles equipped with a central coupler</th>
<th>TEN and similar operation with level crossing</th>
<th>Urban line not isolated from road traffic</th>
<th>Obstacle deflector requirements to be achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision obstacle</td>
<td>Identical train unit</td>
<td>80t wagon</td>
<td>129t wagon</td>
<td>15t deformable obstacle</td>
<td>3t rigid obstacle</td>
<td>Small, low obstacle</td>
</tr>
<tr>
<td>Design collision scenario</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Maintenance machines exempted, locomotives, passenger trains as well as freight wagon are subject to dynamic crashworthiness scenarios. The scenarios proposed in the drafts are close to the European approach: (1) Head-on collision with similar consist, (2) head-on collision with a freight train and (3) impact at level crossing with an obstacle. These scenarios are presented in Table 5.

The freight wagon crashworthiness scenario is more detailed than the locomotive and the passenger rolling stock scenarios but information remains sparse at this stage. The Australian standard seems to be the only standard providing performance scenarios for freight wagons. Locomotive and passenger performances are not yet described in term of velocities, mass, conformity criteria or any other metrics. The operational environment is not part of the description and no information is available on the characteristics of the obstacles in terms of length, mass, contact conditions with the ground, etc.

**In Europe**, design scenarios in EN12663 are established in the context of basic structural requirements, trying to give as much flexibility as possible to train designers for innovation. This aspect appears in a set of design standards having notable lower values than provided in the US standard. The basic design requirements are augmented in the standard EN15227 (European Committee for Standardisation 2008) through performance scenarios. These scenarios must be validated in addition to the design scenarios, in contrast with the US approach.
Performance is assessed using four collision scenarios, selected outcomes of accident statistics carried out in UIC Passenger Commission 1997. It includes a front end impact between two identical train units, a front end impact with a different type of railway vehicle, a train unit front end impact with a large road vehicle on a level crossing and finally a train unit impact into a low obstacle. A detailed table in European Committee for Standardisation 2008 gives train configurations and velocities and is reproduced in this document in Table 6. Depending on the environment and the vehicle classification, the scenarios involve different speeds and/or different collision obstacles.

For the US, design scenarios are presented in 49CFR238. They are more detailed and more evolved than European or Australian standards. Different sets of static loadings are considered depending on the structure of the vehicle. Compared to Australian and European loadings, the US standard assesses horizontal loading up to 15 degrees from the longitudinal axis. Vertical loading and combined loading are given at positions in the horizontal and vertical plan of the front end of the vehicle being tested. The standard restricts the structural geometry of the front end in terms of the number and position of collision posts and corner posts.

Performance scenarios for Tier-I vehicles (see section 2.2) were introduced as part of an update of the 49CFR238 standard. In Appendix F of FRA 2010, the scenario is described as an alternative dynamic performance requirement for front-end structures of cab cars and MU locomotives. Vehicles that comply with the requirements of this Appendix do not need to pass static loading tests. This is in contrast to the European or Australian standard requiring conformity to both design and performance standards. Tier-II vehicles are subject to crashworthiness standards but few details are provided in FRA 1997 or APTA 2006 apart from energy absorption considerations at different sites of a consist. Since neither Australian standards nor European standards consider high-speed impacts, the gap analysis does not refer to this aspect in the following.

2.3.2. Analysis

Australia, European Nations and the US all have design and performance scenarios in application or in a provisional form.
Flexibility in Europe: European standards are flexible regarding design, aimed at providing basic structural rigidity and safety in normal operations and trying to leave freedom of design to manufacturers. In addition to design standards, European railway vehicles are subject to performance validation. European standards are detailed in regard to performance crashworthiness. By separating cases by environment and adapting the test conditions accordingly, the standard allows flexibility on future designs and limits too restrictive standards.

Self-certification in the US: US design standards are very detailed, taking into consideration particular aspects of a vehicle design and testing particular components of the structure. US standards are more restrictive, and they impose structural arrangements regarding the front end of a vehicle. Historically, the design standard was supposed to ensure safety in the event of a collision and is self-certifying: compliance to the 49CFR238 design standard is sufficient for crashworthiness validation. However it is noted that the amendment of January 2010 improves design flexibility through the performance scenario of cab-cars and MU locomotives. This performance scenario is self-certifying and sufficient for crashworthiness validation. There is a difference of philosophy between US standards and European standards, mainly due to the historical development of both standards.

Compromises in Australia: Australia’s draft scenarios are based on the US standards for design assessment and are more focused on the European standards for performance evaluation by using three similar scenarios. At this stage, the performance scenarios do not provide details of the procedure for applying for assessment, nor do they provide measures of success. In its current form, there seem to be conflicting ideas in the Australian standards due to the focus on US design standards on the one hand and European performance standards on the other. Since the US standards are self-certifying, they are more restrictive in practice. The use of an equivalent set of requirements in the Australian standards would indicate that performance scenarios are not necessary or would be redundant. In addition, requiring a vehicle to comply to US-like design standards in combination with European-like performance standards imposes more restrictions on manufacturers’ designs to pass both tests. Design standards would lead potentially to heavier vehicles (US trains are on average 25% heavier than their European counterparts) to resist higher static loading while performance would be better with a lighter design.
Lateral performance scenarios: Currently there are no dynamic performance scenarios considering the lateral impact between rolling stock and an obstacle in either of the standards reviewed. However, static considerations are present in the Australian and US standards through side loading and roof loading.
3. Certifications

3.1. Design standards

3.1.1. Overview

In Australia, loading cases applied to vehicles from the AS7520 series are summarised in Table 7.

Table 7: AU - Design evaluation

<table>
<thead>
<tr>
<th>Loading</th>
<th>Locomotives</th>
<th>Passengers</th>
<th>Freight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
<td>Medium</td>
<td>Light</td>
</tr>
<tr>
<td>Compression</td>
<td>4450kN</td>
<td>3500kN</td>
<td>2000kN</td>
</tr>
<tr>
<td></td>
<td>DCCAU-I</td>
<td>DCCA-U-I</td>
<td>DCCAU-I</td>
</tr>
<tr>
<td>Tension</td>
<td>3375kN</td>
<td>2700kN</td>
<td>1500kN</td>
</tr>
<tr>
<td></td>
<td>DCCAU-I</td>
<td>DCCA-U-I</td>
<td>DCCAU-I</td>
</tr>
<tr>
<td>Longitudinal Anti-climb</td>
<td>1000kN</td>
<td>1000kN</td>
<td>1000kN</td>
</tr>
<tr>
<td></td>
<td>DCCAU-II</td>
<td>DCCAU-II</td>
<td>DCCAU-II</td>
</tr>
<tr>
<td>Collision post</td>
<td>2250kN @ 0mm</td>
<td>1000kN @ 0mm</td>
<td>275kN @1650mm if 4 posts or 550kN if 2 posts + 90kN lateral force. DCCAU-V</td>
</tr>
<tr>
<td></td>
<td>890kN @ 760mm</td>
<td>445kN @760mm</td>
<td>n.a</td>
</tr>
<tr>
<td></td>
<td>DCCAU-III</td>
<td>DCCAU-III</td>
<td>DCCAU-V</td>
</tr>
</tbody>
</table>

n.a.
<table>
<thead>
<tr>
<th>Vertical</th>
<th>Self-weight</th>
<th>Maximum gross mass on rail without exceeding one half of the yield stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupler</td>
<td></td>
<td>220kN upward and downward load DCCAU-I</td>
</tr>
<tr>
<td>Anti-climb</td>
<td>890kN DCCAU-I</td>
<td>220kN DCCAU-I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200kN DCCAU-IV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>n.a</td>
</tr>
<tr>
<td>Rollover</td>
<td>Should support half the mass with bogies when on the roof. DCCAU-I</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Should support the fully loaded mass with bogies when on the side. DCCAU-VI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>n.a</td>
<td></td>
</tr>
<tr>
<td>Cowcatchers</td>
<td>See table # for cowcatchers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>n.a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>n.a</td>
<td></td>
</tr>
</tbody>
</table>

Maintenance vehicles are not presented in the table, they are considered out of the scope of this document.

Conformity criteria are summarised in Table 8, and the conformity codes are used as references in Table 7. There are six conformity criteria in the AS7520 standards - they are based on stress within the material and sometimes include parts of the vehicles (e.g. body members, main structural members) to be assessed with the element being tested. Both longitudinal and vertical loadings are present, applied to precise elements of the vehicle such as anti-climb, collision post, or couplers. Two conditions of lateral loading exist in the draft for passenger vehicles, as well as a scenario with the passenger car on its side. Cowcatchers are defined by direct reference to European standards.

The Australian standard specifies loadings on different classes of vehicle by literally combining the overseas requirements. European standards are used for passenger consists where relevant; US standards are applied where there are gaps in the European standards. The use of European conditions on passenger vehicles instead of US standards may be so as to increase design flexibility for incorporation of CEM designs and allow for lighter train units.
The notion of flexibility is present in the standard, for example there is reference to the possibility of shaping the collision post to comply with the overall line of the train. For medium locomotives, the standard makes use of the US loading amplitudes whereas heavy locomotives and freight wagons are subject to noticeably higher stress than both US and European standards. The reason for higher loadings for these vehicles may be related to the train's size in Australia. Loading conditions for passenger cars on collision posts are equivalent to the loading required on locomotives in the US.

However, stiffness of heavy vehicles and passenger cars/light locomotives varies by a factor of two to three depending on the element being tested. This particularity of the Australian standard may lead to issues in developing performance standards, especially for the passenger train/freight train collision scenario.

On the one hand, this aspect could result in the development of better and more innovative CEM designs. On the other hand, it could result in costs for the manufacturer exceeding what would be desirable. It is difficult to estimate the impact of the difference of stiffness between heavy and light consists. It would be interesting for the CRC-crashworthiness project to clarify this issue through modelling and provide a better insight on the matter.

Table 8: AU - Design conformity criteria

<table>
<thead>
<tr>
<th>Design conformity criteria reference</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCCAU-I</td>
<td>Without exceeding the critical design stress</td>
</tr>
<tr>
<td>DCCAU-II</td>
<td>Without exceeding the safe-working stress</td>
</tr>
<tr>
<td>DCCAU-III</td>
<td>Without exceeding the ultimate strength of the material</td>
</tr>
<tr>
<td>DCCAU-IV</td>
<td>Without exceeding one half of the yield stress of the material</td>
</tr>
<tr>
<td>DCCAU-V</td>
<td>Without exceeding the critical design stress of any vehicle body member</td>
</tr>
<tr>
<td>DCCAU-VI</td>
<td>Without exceeding the critical design stress in the main structural</td>
</tr>
</tbody>
</table>
For Europe, design standards are discussed in European Committee for Standardisation 2000 and summarised in Table 9.

The intent of the document is to provide basic structural integrity. The standard considers only the strength of the vehicle structure without considering elements such as anti-climbers and does not restrict the architecture of the vehicle itself. There is no mention of collision posts or corner posts, nor any notion of lateral loading. The standard is general and allows flexibility in the design.

The conformity criteria are clear: a single criterion for all tests, based on three stress ratios that must be bigger than or equal to a security coefficient. For each loading case, the ratio of the yield stress with the current stress must be bigger than or equal to the security coefficient.

If the design is also limited by the ratio of ultimate stress or buckling stress to the current stress, these must be satisfied as well. Any static strength must be demonstrated by calculations and/or testing. There must be no permanent deformation or fracture of the structure as a whole, or any individual element under the application of the design loading cases.

The EU standard is only a part of crashworthiness certification and may be interpreted as being related to critically low events for the vehicles.
Table 9: EU - Design evaluation

<table>
<thead>
<tr>
<th>Longitudinal</th>
<th>Freight</th>
<th>Passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-I</td>
<td>F-II</td>
</tr>
<tr>
<td>Compressive at buffer level and/or coupler level</td>
<td>2000</td>
<td>1200</td>
</tr>
<tr>
<td>Compressive below buffer level and/or coupler level</td>
<td>1500</td>
<td>900</td>
</tr>
<tr>
<td>Compressive applied diagonally at buffer level if side buffers are fitted</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Tensile in coupler area</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>Compressive 150mm above the top of the structural floor at head stock</td>
<td>-</td>
<td>400</td>
</tr>
<tr>
<td>Compressive at the level of the waistrail</td>
<td>-</td>
<td>300</td>
</tr>
</tbody>
</table>
In the United States, §238.211 Collision posts and §238.213 Corner posts from the 49CFR238 standard were updated and described in FRA 2010. The update modifies or completes load position, orientation and magnitude. A summary of the standard is given in Table 11 and design compatibility criteria are given in Table 10. The US standard assesses crashworthiness through the application of a number of loadings on the vehicle. The updated version of January 2010 includes horizontal loading ranging from longitudinal to lateral loading and prescribes vertical loading. Loading exists at various heights of the frames and particular attention is given to collision posts and corner posts.

Table 10: US - Design conformity criteria

<table>
<thead>
<tr>
<th>Design Conformity Criteria Reference</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCCUS-I</td>
<td>Without permanent deformation of the body structure</td>
</tr>
<tr>
<td>DCCUS-II</td>
<td>Without permanent deformation</td>
</tr>
<tr>
<td>DCCUS-III</td>
<td>Without failure</td>
</tr>
<tr>
<td>DCCUS-IV</td>
<td>Without exceeding the ultimate strength</td>
</tr>
<tr>
<td>DCCUS-V</td>
<td>Without exceeding the ultimate strength of either the post or its</td>
</tr>
</tbody>
</table>
Loadings are higher in magnitude and test the vehicle more thoroughly than in the European standard. The standard imposes structural design on collision and corner posts.

The static loading tests establish a complete crashworthiness certification without the need for dynamic considerations. This aspect of the US design standard is unique in the standards reviewed. However the approach is detrimental to more modern vehicles including CEM equipment.

In order to assess vehicles with such equipment, the standard provides an alternative to the static loading using dynamic testing; explicitly stating that only one of the forms needs to be validated.

The dynamic facet of the standard is presented in more detail in chapter 3.2 of this document.

**Table 11: US - Design evaluation**

<table>
<thead>
<tr>
<th>Loading</th>
<th>Passenger car</th>
<th>Locomotives</th>
<th>MU Locos</th>
<th>Cab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal, compression on line draft.</td>
<td></td>
<td>3559kN - DCCUS-I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical, upward and downward on anti-climbers</td>
<td>445kN DCCUS-II</td>
<td>890kN DCCUS-III</td>
<td>445kN DCCUS-II</td>
<td></td>
</tr>
<tr>
<td>Vertical, downward from coupler shank on coupler carrier.</td>
<td></td>
<td></td>
<td></td>
<td>445kN - DCCUS-II</td>
</tr>
<tr>
<td>Collision posts ultimate longitudinal shear strength at a point even with the top of the underframe to which it is attached</td>
<td></td>
<td></td>
<td></td>
<td>1335kN</td>
</tr>
</tbody>
</table>
### Gap analysis of crashworthiness standards

| Longitudinal on collision posts at a point even with the top of the underframe. | - | 2224kN - DCCUS-IV on joint |
| Longitudinal on collision posts at a point at 762mm above underframe | - | 890kN - DCCUS-IV on joint |
| Longitudinal on collision posts at any height above underframe | - | - | 267kN - DCCUS-VI |
| Horizontal on full height corner posts at a point even with the top of the underframe. | 668kN - DCCUS-V | 1335kN – DCCUS-V |
| Horizontal on full height corner posts at 457mm above the top of the underframe. | 134kN - DCCUS-V | 4455kN – DCCUS-V |
| Horizontal on full height corner posts at the point of attachment to the roof structure. | 89kN - DCCUS-V | LO: 133kN |
| Horizontal on full height corner posts at any height above the top of the underframe. | - | 200kN |
| Rollover strength | Able to rest on its side, uniformly supported at the roof rail, the side sill frame. Able to rest on its roof under DCCUS-VII |

**Side posts and corner braces:** (For modified girder or semi-mono-coque construction)

**Longitudinal:** the sum of the section moduli in cubic inches taken at the weakest horizontal section between the side sill and the side plate of all posts and braces on each side of the car located between the body corner posts shall be not \(< 0.3 \times \text{the distance between the end-plane centres.} \)

**Transversal:** The sum of the section moduli in cubic inches taken at the weakest horizontal section between the side sill and the side plate of all posts, braces and pier panels, to the extent available, on each side of the car located between body corner posts shall not be less than \(0.20 \times \text{the distance in feet between the centres of the end panels. The centre of an end panel is the point midway between the centre of the body corner post and the centre of the adjacent side post.} \)
3.1.2. Analysis

Basic design requirements in Europe: As stated in the introduction of the European design standard: “the aim is to allow designer freedom to optimise his design whilst maintaining requisite level of safety. It defines no arithmetical techniques in order not to affect the developments in analysis methods and permit innovative developments by vehicle designers and operators” (European Committee for Standardisation 2000). As a consequence, crashworthiness considerations are best evaluated in the complementary document (European Committee for Standardisation 2008) of the standard.

Complete assessment in the US: The US chose to provide a self-certifying design standard to fully assess crashworthiness without the need for dynamic testing if the operator/manufacturer consortium wishes to do so. Following this approach, it is natural that static loading are higher and stress the structure more thoroughly. However the standard imposes more restrictions on the design of the framing and leads to heavier trains. A new set of regulations for Tier-I passenger trains gives a dynamic testing alternative allowing new designs and CEM equipped vehicles. In that case the static loading test is not required.

Issues in Australia: For passenger trains, the Australian draft standard follows European criteria when available, augmented by US standards when no details exist in European documents. For example, the draft gives specifications related to US standards for lateral loadings on passenger trains that are absent in the European standards. Loads are equal to or half US requirements on the collision posts for most vehicles. However, heavy locomotive loadings are twice to three times the value applied to passenger vehicles. It appears possible that such a difference in stiffness leads to complications in head-on collisions between heavy locomotives and passenger consists. Energy absorption requirements may be difficult to meet on light locomotives. The issue needs to be clarified in more detail through modelling to quantify whether or not the current requirements are practical. Once a proper analysis has been carried out, a set of recommendations would be given to the RISSB. It is envisaged that such recommendations would fall into one of these three categories:

- Lower static requirement for heavy vehicles or put an upper boundary such that light vehicles can safely handle the collision
- Increase light vehicles’ static requirements
- Provide an indication that current or future CEM designs would provide energy absorption capabilities adequate for passenger safety at a cost bearable by the rail industry.
3.2. Performance standards

3.2.1. Overview

The Australian draft does not provide indications on length, mass, velocities, brake state or track conditions on any of its passenger vehicle scenarios. Nonetheless, the standard provides indications of the criteria that need to be defined such as maximum deceleration and allowed area of collapse. It requires the use of crash energy management devices on locomotives and passenger trains. At this stage, performance standards are in line with the European prescription.

The European standard defines various types of vehicle and obstacles related to the environment of statistically major incidents. Only passenger trains and locomotives are part of the standard. Reference trains are used in assessing locomotives, power heads, driving trailers and coaches that do not form part of a fixed rate of vehicles. Details on the length, mass and configurations are provided. Each scenario, for each vehicle classification, prescribes a velocity test; not all vehicles are relevant to all scenarios as detailed in Table 6. As stated in European Committee for Standardisation 2008, "passive safety objectives are given for a complete train unit. It is impractical to evaluate the complete train unit’s behaviour by testing, therefore the achievement of the objectives can be validated by dynamic simulation, which corresponds to each of the design collision scenarios. The use of numerical simulation alone is sufficient for accurate prediction of structural behaviour in areas of limited deformation. However, for areas of large deformation only, the validation program includes the validation of the numerical models by appropriate tests (combined method). The "combined method" is described in the Appendix.

Anti-climbing devices are assessed in performance standards. Compared to other countries, testing the anti-climbing system in dynamic scenarios not only evaluates its strength, it also evaluates its capability to engage and limits overriding through a metric associated with the vertical displacement of the train estimated at the wheel-rail interface. The European standard emphasizes the function of the anti-climb and its steadiness in a crash instead of its static rigidity as presented in the other standards.

Survival spaces must remain intact during the full collapse of the energy absorbing elements but at the same time limit local plastic deformation and local buckling. "The reduction in length of passenger survival spaces must be less than 50mm over any 5m length or the plastic train must be limited to 10% in these areas". This aspect of the standard is unique in the review. It permits survival spaces to absorb
part of the collision energy. Such flexibility may lead to energy management devices within the survival space. Since survival areas represent the major part of a vehicle, potential and noticeable increases of the overall energy absorption capability of a consist may be achieved. The standard requires a survival space for the driver and other cab occupant represented by a zone around each fixed seat.

The mean longitudinal deceleration in the survival spaces is limited to 5g for scenario 1 and scenario 2 and 7.5g for scenario 3.

**For the US**, Dynamic crashworthiness is essentially considered through level crossing scenarios. The evolution of the standards is incremental and current research on the matter seems related to a programme started in 1999 (Jacobsen & Tyrell 2003), (Llana 2009).

FRA 2010, an update of the 49CFR238 standard, introduces a dynamic crashworthiness standard for Tier-I passenger equipment for front end structures of cab cars and MU locomotives. The validation of the performance requirements is in lieu of the static requirements for collision posts and corner posts. As stated in FRA 2010, the performance requirements are intended to be equivalent to the static cases and put in place to help in evaluating cab cars and MU locomotives with shaped noses and/or CEM designs. The end structure must be designed to protect the occupied volume for its full height, from the underframe to the anti-telescoping plate or roof rails. The standard does not specify a particular velocity and rather bases the test on the minimum energy involved during the impact.

In 49CFR229, dynamic crashworthiness is assessed with two full-sized tests on freight locomotives. The decisions made on the obstacles (steel cylinder, steel slab) are historical, related to the 1998 accident at Portage Indiana, (Jacobsen & Tyrell 2003).

### 3.2.2. Scenario 1: Collision with identical consist
Crashworthiness requirements are not yet in place in the draft standards for passenger vehicles in Australia. For freight vehicles, the standard specifies a range of velocities to be applied during the test starting at 10km/h by 3km/h increments up to 20km/h or when a coupler force of 5500kN is reached - see Table 5.
All categories of vehicles defined in the European standard must comply in a head-to-head collision with velocities ranging from 15 to 36km/h depending on the category. Velocities are relatively low in the scenario. One explanation for such velocities may be related to the active anti-collision systems available in Europe that reduce the eventuality of higher speed collisions. A second explanation may be related to the outcome of the accident statistics giving a low occurrence of collisions at higher speeds.

There are no dynamic collision scenarios of identical train units defined yet in the US. Crashworthiness is evaluated via static testing or collisions with an obstacle other than a railway vehicle.

3.2.3. Scenario 2: Collision with freight vehicle or large consist

For a collision between a train unit and a buffered wagon, the European standard refers to an 80t wagon having only one degree of freedom in the translational x direction and the interface geometry as shown in Figure 1. The end wall is supposedly rigid. It is equipped with side buffers as described in the figure, a stroke of 105mm and a force-displacement characteristic indicated in Figure 2. The consideration of a rigid wagon minimises the issue related to stiffness differences in a Freight-Passenger train collision scenario by assigning a “worst case” scenario since the majority of the energy needs to be absorbed by the vehicle being assessed. The presence of the buffers on the wagon increases the accuracy of the scenario by allowing part of the energy to be elastically transferred to the wagon and provides a more realistic mean to transfer energy at the early stage of the contact.

![Buffered wagon interface](image1.png)

![Wagon buffer characteristic](image2.png)

For C-III vehicles only, a regional train is represented by a rigid mass of 129t having one degree of freedom in the translational x direction and a rigid vertical face. The coupler has the dimensions shown in Figure 3 and an energy absorption capacity of 530kJ, see Figure 4. While the regional train is rigid, it
includes an energy absorption system. As for the 80t wagon obstacle, it sets a “worst case” scenario in perspective (rigidity of the obstacle) while considering the reality of the collision. The CEM lowers the energy absorption capability requirement on the vehicle tested leading to potentially lighter C-III vehicles.

There are no dynamic collision scenarios of identical train units defined yet in the US or Australia.

3.2.4. Scenario 3: Collision at level crossing

The Australian environment has road trains, which are notably longer and heavier than trucks operating in Europe or the US. Road trains range from 62.5T to 147T in weight and 26 meters to 53m in length. The majority travel with loadings between 80T and 120T. The maximum speed is 90km/h in most states and less than 100km/h otherwise. For comparison, trucks are about 40T and 18m in Europe. Road trains represent a serious risk to the passenger/ freight trains due to their length, low acceleration and time needed to go through a level crossing from a stationary position.

In 2006, an accident occurred involving the Ghan passenger train and a road train at the Ban Ban Springs level crossing in the Northern Territory. At the time, the road train was hauling two empty lorries for a total of 27 meters and 26T. However, the road train was legal for a haul combination up to 53m in length and 140T (ATSB 2006). Due to the length of a road train and its articulations, lorries tend to swipe and hit the sides of a train unit, see Figures 7 and 8. This characteristic may need to be investigated and an eventual suggestion made for inclusion in AS7520. Obstacle deflector (cowcatcher in Australia)
standards are based on the European standard, and test conditions need to be investigated for Australian conditions. In particular, compliance to an impact involving cows or camels should be evaluated since these large animals can wander freely in the Australian countryside.

In Europe, a collision between a train unit and a large heavy obstacle at a level crossing takes the form of a complete numerical model without the possibility of real testing due to the characteristics of the obstacle. The latter is unrestrained as illustrated in Figure 9. It is defined in terms of geometry, mass and centre of mass. The stiffness of this obstacle is given in Figure 10 when impacted at its centre by a solid, uniform sphere under specific conditions.

In this scenario the model implies that part of the energy will be absorbed by the trailer. The contact trailer-assessed vehicle is non-local and stresses the overall front end design of the vehicle; it does not test a particular part of the structure. This approach is advantageous as it allows very different structures to be evaluated but introduces a level of complexity in the modelling and in the analysis. A more detailed and quantitative analysis of this scenario was carried out in Llana 2009.
The US scenario assessment is in principle a condition similar to scenario 3 of the European standard EN15227. However the obstacle, energy and contact conditions are very different (Llana 2009). Two cases are presented in FRA 2010: one for dynamic testing of a collision post and one for dynamic testing of the corner post. The introduction of this section of the standard is intended to provide more flexibility in the design of passenger vehicles and development of CEM designs. In both cases (collisions and corner posts) the tests need only to represent the front-end frame of the vehicle. There are no requirements for a full vehicle body structure representation. There are no restrictions on the mass of the vehicle to be tested because it is initially stationary. There are no restrictions on the speed of the proxy to be used for impact. However, geometric considerations are given as well as the position of impact with the posts. Velocities and mass are indirectly prescribed by a minimum amount of energy to be involved during the test. Figure 11 and Figure 12 illustrate the scenarios for a collision post and corner post.

The fact that the full body structure is not required in the test tends to suggest that the US standard puts all the safety requirements on the very front end of the vehicle. There is no information available on the level of deformation allowed in parts of the vehicles such as the temporary occupancy areas. Collision and corner posts have maximum deformation allowed towards the inside of the vehicle without complete separation of the posts at their connections with the rest of the structure; they must absorb 0.18J and 0.16J respectively. The nominal weights of the obstacle and the cab car or MU locomotive, as ballasted and the speed of the obstacle may be adjusted to involve at least the minimum energy to be absorbed ($E_a$) by the posts, in accordance with an energy based equation.
For freight locomotives, the US proposes two scenarios presented in 49CFR229. The first scenario involves the front-end structure of the locomotive. It must withstand a frontal impact with a proxy object which is intended to simulate loading carried by a heavy highway vehicle. In this scenario, the obstacle has a cylindrical shape of 1200mm in diameter and a length of 3150mm with a minimum mass of 29,483kg uniformly distributed - see Figure 13. In a 48km/h impact, the front-end structure of the locomotive must result in no more than a total of 600mm inward deformation and no more than 300mm of intrusion into the cab.

The second scenario involves an oblique impact with an obstacle “intended to simulate an intermodal container offset from a freight car on an adjacent parallel track”. In this scenario, the obstacle has a block shape of 36 inches in width, 60 inches in height, 108 inches in length for a minimum weight of 29,483kg uniformly distributed. In a 48km/h impact, the front-end structure of the locomotive must result in no more than a total of 1500mm inward deformations and no more than 300mm of intrusion into the cab - see Figure 14.

3.3. Analysis

State of the Australian performance standard: The Australian draft does not provide indications on length, mass, velocity, brake state or track conditions for any of its passenger vehicle scenarios. The
performance part of the Australian standards is a work in progress giving few details at this stage on the scenarios and their assessment. The actual content is based on the European performance standard and needs to be thoroughly investigated for adequacy with Australian conditions.

**Australian road trains:** These trucks are notably longer and heavier than trucks operating overseas. In the case of a level crossing scenario involving a lorry as depicted in the European standard, adjustment will need to be made to better integrate Australian road trains. Due to the length of road trains and their articulations, Lorries can potentially swipe and hit the sides of a train unit. After evaluation of the statistical risk associated with road trains, the CRC R3.114 project should quantify the level of energy of impact on train sides due to the swipe motion of a trailer. The obstacle deflector standard, currently based on the European standard by reference, needs to reflect Australian conditions: the impact involving cows or camels should be evaluated since these large animals can wander freely in the Australian countryside (Edwards et al. 2008).

**European particularities:** The European performance standard makes heavy use of Finite Element Analysis in validating vehicle crashworthiness for passenger vehicles. Because of the importance of modelling, a complete protocol was established to validate the models themselves. This phase of the conformity process is crucial in the standard. While it involves a consequent amount of work to calibrate energy absorption mechanisms, this does not need to be repeated for all new vehicles. Every system previously validated that provides a calibrated model can be readily implemented in new vehicle models. A collision at a level crossing takes the form of a complete numerical model without the possibility of real testing due to the characteristics of the obstacle. Part of the energy will be absorbed by the trailer in a non-local impact that stresses the overall front-end design of the vehicle. This approach allows very different structures to be evaluated but introduces a level of complexity in the modelling and in the analysis.

Anti-climb devices are assessed in performance standards. The European standard emphasises the function of the anti-climb and its steadiness in a crash instead of its static rigidity.

Survival spaces are allowed to deform, albeit by a small amount. Since survival areas represent the major volume of a vehicle, potential and noticeable increases of the overall energy absorption capability of a consist may be achieved.
The European standard puts an upper boundary on head-to-head impact with other railroad vehicles by assuming a rigid obstacle vehicle. In order to provide a more realistic approach of the contact conditions it superimposes either functional buffers or CEM systems on the obstacle.

**Performance assessment by level crossing scenarios:** In the US, the validation of the performance requirements is in lieu of the static requirements for collision posts and corner posts. The US standard is not based on impact velocity but rather on minimum energy involved. The criterion regarding absorbed energy is the same for all passenger vehicles of class Tier-I, without differentiation on the operational conditions.

The obstacles involved in the level crossing scenarios of 49CFR238 test local vehicles at collision and corner posts. The full body structure does not need to be reproduced; the test tends to suggest that the standard puts all the safety requirements on the very front end of the vehicle. There is no information available on the level of deformation allowed in part of the vehicles such as temporary occupancy areas.

Since the Australian standards allow shaped corner posts and collision post to comply with the overall line of the vehicle, the impact in such a scenario can lead to climbing of the proxy with variable results amongst vehicles of different shapes. It is particularly problematic for full-size testing considering the cost of a single test. Even though a simulated approach is not presented in the standard, the scenario may have benefit in such a context due to its simplicity, the localization of the impact and the advantage of repeatability inherent in models.

Freight locomotives are assessed in 49CFR229 with two scenarios. The scenarios are similar to those in 49CFR238 as they submit the vehicle to a centred loading and an offset loading. The obstacles are however specific, using a 30T cylinder and a 30T parallelogram. The choice of scenarios seems historic and related to previous accidents occurring in the US; they may not necessarily represent the most statistically occurring situations.
4. Findings

Development of an operational classification of vehicle: The AS7520 draft does not provide indications regarding the environment of a service. Crashworthiness scenarios should reflect this aspect to consider real dangers and avoid unnecessary design constraints on consists not being subject to such hazards. It is suggested that the development of Australian crashworthiness scenarios be preceded by an environmental/operational classification based on the outcome of the statistical analysis of railroad accidents. This would help in defining more precisely crashworthiness variables such as mass, velocities, reference vehicles and obstacles.

Conflicts and mutuality of certification criteria: Certification aspects need to be investigated at several levels. It was found that loadings and criteria are mostly derived from overseas standards. In the current form the draft seems to have conflicting ideas due to the focus on US design standards on the one hand and on European performance standards on the other. US design standards are self-certifying for passenger vehicles - the use of equivalent loadings in the Australian standard would indicate that the definition of performance scenarios is not necessary or is redundant, unless performance is presented as an alternative. This aspect needs to be clarified to understand whether or not redundancy is suitable or should be avoided.

Design of locomotives: Heavy locomotive loadings are currently twice to three times that of passenger vehicles. It appears possible that such a difference in stiffness leads to complications in head-on collisions between heavy locomotives and passenger consists. As a result, energy absorption requirements may be difficult to meet on light locomotives. The issue needs to be clarified through modelling to quantify the practicality of current requirements.

Validation of obstacle deflectors: Obstacle deflectors, currently based on European standards by reference, need to reflect Australian conditions: the impact involving cows or camels should be evaluated since these large animals can wander freely in the Australian countryside.

Anti-climbing scenario: The Australian standard makes use of scenarios close to the European performance document. The latter emphasises the function of the anti-climb and its steadiness in a
Gap analysis of crashworthiness standards

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crash instead of its static rigidity. If performance requirements follow a European approach, anti-climb mechanisms would preferably be tested dynamically instead of statically. Metrics based on anti-climb effectiveness in dynamic conditions should be presented (height of wheel sets at impact, longitudinal and lateral stabilities).

Road-trains: The peculiarity of the Australian environment is the existence of road trains, being notably longer and heavier than trucks operating in Europe or the US. In the case of a level crossing scenario involving a lorry as depicted in the European standard, adjustment will need to be made to better integrate Australian road trains. Due to the length of road trains and their articulations, Lorries can potentially swipe and hit the sides of a train unit. The Ban Ban Springs level crossing incident of 2006 is an example of this problem. After evaluation of the statistical risk associated with road trains, the project should quantify the level of energy of impact on train sides due to the swipe motion of a trailer and eventually propose a scenario of lateral impact due to trailer swiping.

Applicability of scenarios for shaped posts: The Australian standards allow shaped corner posts and collision posts to comply with the overall line of the vehicle. The impact from a US scenario with a proxy can lead to climbing of the proxy with variable results amongst vehicles of different shapes. It is particularly problematic for full-size testing considering the cost of a single test. Even though a simulated approach is not presented in the US standard, such a scenario may be beneficial in modelling due to its simplicity, the localization of the impact and the advantage of repeatability inherent in models. Currently, the Australian standard does not refer to such a specific scenario. A deeper analysis could show advantageous aspects of this approach.

Assessment criteria: Once scenarios are clarified, assessment criteria should be investigated in detail. Survival spaces are allowed to deform by a small amount in Europe but not in the US. Since survival areas represent the major volume of a vehicle, potential and noticeable increases of the overall energy absorption capability of a consist may be achieved. Compression of a few percent within survival spaces seems reasonable and is not likely to present a threat to passengers by volume reduction but may reduce the maximum deceleration they experience.

Definition of validation procedures: The validation procedure is lacking in the AS7520 series. A decision needs to be made whether full testing or partial testing is required. Also the place of modelling in the
standard needs clarification. Because of the importance of modelling in the European standard, a complete protocol was established to validate the models themselves. This phase of the conformity process is crucial in the standard. In the case of a simulation approach in Australia, a full programme for model calibration of high deformation areas and systems should be created. A full programme for final model validation should also be designed.
5. Conclusions

In Australia, the Rail Industry Safety and Standards Board (RISSB) is developing a new set of standards for the railway industry. In particular, the standard AS7520 is a draft aimed at providing national crashworthiness specifications for Australia. The CRC rail project R3.114 provides some insight on overseas standards and makes suggestions regarding AS7520. Crashworthiness standards are based on historical evolution of the railway industry and accident statistics, as well as environment and vehicle classifications from which crashworthiness scenarios are derived. Conformity criteria are defined based on bio-mechanical principles for passenger survivability and minimum permissible volume in survival areas.

A literature review highlighted a set of standards from these overseas countries/unions relevant to the crashworthiness of passenger vehicles and locomotives. In this document we analysed these standards and highlighted the differences amongst them. Gaps between the standards are the result of differences in environmental operations (technical), variations in accident statistics (historical) as well as differences in assessing passenger safety (political/philosophical). However, standards pursue the same goal: passenger safety.

The AS7520 refers explicitly to the overseas standards. It was found that the scenarios, loadings and criteria are mostly derived from the overseas standards. In its current form there seem to be conflicting ideas in the Australian standard due to a focus on US design standards on one hand and on European performance standards on the other hand. In Europe, design standards and performance standards are complementary, crashworthiness being mostly evaluated through numerical simulation and impacts generally involving distributed contacts. In the US, design standards and performance standards are mutually exclusive; they are validated through real-life testing and stress the structures locally.

Several aspects were highlighted in this document and suggestions are made in the CRC R3.114 project to better understand what parts of the draft may need adjustment to successfully produce crashworthiness standards for the Australian railway industry and environment. Amongst others, environments of a service, impacts due to road-trains and validation procedures will need further work during the course of the project before suggestions can be made to the RISSB. The project needs more
information to comment on perceived inconsistencies. Most of the modifications and suggestions for
the future can only be established through statistical analysis, simulation and testing.
6. Appendix

A. Procedure for modelling validation in the European standard

The combined method consists of a series of full scale tests of crumple zones and energy absorbing devices such as inter-vehicle devices, energy absorption elements and anti-climbing devices. The tests should normally absorb 80% of the maximum energy required to be absorbed by the mechanism being tested and should have sufficient energy to ensure that all the mechanisms included in the test are initiated. The purpose is to validate important parts of the energy absorption system and use output data for model calibrations. The second step calibrates the numerical model of the structure by analysing the behaviour of the energy absorption devices and crumple zones in light of the tests. The sequence of the phenomena of energy absorption should be equivalent. The third step defines the numerical simulation of the design collision scenarios. A 3D model of each type of vehicle structure that will be subjected to permanent deformation must be created. This model includes the calibrated model of the driver’s cab or vehicle end deforming structures and a complete 3D model of the rest of the body car structure. Normally only the first or the first two vehicle models incorporate energy absorbing elements and the deforming structure in detail. The remaining part of the consist can be represented as a lumped mass/spring system representing overall behaviour.

Once the final model is calibrated, it must go through a test program. The latter validates if the final model correctly reproduces the behaviour of the energy absorbing mechanisms. The tests should reflect the energy absorption requirements of scenario 1 or scenario 2 where these apply to the design, but this requirement does NOT require the actual scenario to be reproduced exactly in the tests. The modelling is considered to be acceptable if, when compared to the tests, the same sequence of events occurs during the collision (i.e. where several phases of energy absorption occur they correspond), the same observed deformation patterns occur, the level of energy dissipated by the model is within 10% of the test value, and the simulation produces a global forces curve which exhibits the same general characteristics as measured in the test.

B. Australian environment: Risk assessment

Wandering animals such as camels, kangaroos and cows. Large vehicles (road trains), passive level crossing without fencing, sand storm, rainforest (large trees), rocks, what about steel coils on wagons,
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