Taylor & Francis
Taylor & Francis Group

Disability and Rehabilitation: Assistive Technology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/iidt20

Entrapment and extraction of wheelchairs at flange gaps with and without flange gap fillers at pedestrian railway crossings

Kevin Farries, Matthew Baldock, James Thompson, Christopher Stokes & Carolyn A. Unsworth

To cite this article: Kevin Farries, Matthew Baldock, James Thompson, Christopher Stokes & Carolyn A. Unsworth (2024) Entrapment and extraction of wheelchairs at flange gaps with and without flange gap fillers at pedestrian railway crossings, Disability and Rehabilitation: Assistive Technology, 19:7, 2471-2481, DOI: 10.1080/17483107.2023.2296954

To link to this article: https://doi.org/10.1080/17483107.2023.2296954

DISABILITY AND REHABILITATION: ASSISTIVE TECHNOLOGY
2024, VOL. 19, NO. 7, 2471–2481
https://doi.org/10.1080/17483107.2023.2296954

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS

Check for updates

Entrapment and extraction of wheelchairs at flange gaps with and without flange gap fillers at pedestrian railway crossings

Kevin Farries[a], Matthew Baldock[b], James Thompson[b], Christopher Stokes[b] and Carolyn A. Unsworth[c,d,e,f]

[a]School of Civil Environmental and Mining Engineering, University of Adelaide, Australia; [b]Centre for Automotive Safety Research, University of Adelaide, Australia; [c]Institute of Health and Wellbeing, Federation University, Australia; [d]Department of Rehabilitation, Jönköping University, Jönköping, Sweden; [e]Department of Neurosciences, Monash University, Clayton, Australia; [f]Department of Occupational Therapy, James Cook University, Townsville, Australia

ABSTRACT

Purpose: Where pedestrian crossings meet rail tracks, a flange gap allows the train wheel flanges to pass. This gap can be hazardous for wheelchair users as castor wheels may become trapped. While compressible gap fillers can eliminate the flange gap, fillers are subject to wear, pose a derailment hazard to light rail vehicles and can strip grease from passing wheels. These issues could be mitigated by partially filling the flange gap with a compressible filler. The aim was to investigate the risk of entrapment and ease of extraction of wheelchair castors from flange gaps fully and partially filled with compressible fillers, and assess ride quality.

Materials and methods: Entrapment risk and ease of extraction for four wheelchairs were tested at various crossing angles with flange gap fillers. Twelve wheelchair users tested ease of extraction and ride quality for partially and fully filled flange gaps.

Results: It was found that risk of entrapment is low if a standards-compliant crossing with open flange gaps is traversed in a straight line. However, castors can become trapped if the user alters direction to avoid an obstacle or if the crossing surface is uneven. Once trapped, castors are extremely difficult to remove without external assistance.

Conclusions: Flange gap fillers that reduce the gap to 10 mm or less eliminate entrapment while retaining acceptable ride quality. Filling flange gaps or leaving a residual gap depth of less than 10 mm is the best option to eliminate risk of entrapment and ensure good ride quality for wheelchair users.

ARTICLE HISTORY
Received 13 July 2023
Revised 11 October 2023
Accepted 13 December 2023

KEYWORDS
Wheelchair; safety; flange gap; railway crossing; mobility scooter

IMPLICATIONS FOR REHABILITATION

- Rail crossings flange gaps pose an entrapment hazard for wheelchair users
- Partial or complete flange gap fillers may reduce entrapment but require research
- Rehabilitation professionals need to educate wheelchair users on techniques to cross flange gaps safely
- Consumers and health professionals can consult rail operators to partially fill flange gaps

Introduction

Where a pedestrian crossing meets a rail track, a flange gap is required to allow the train wheel flanges to pass without obstruction. This gap can create a hazard for pedestrians, particularly those using manual or powered wheelchairs or mobility scooters where smaller castor wheels may become trapped in the flange gap [1–7]. The collective term "wheelchairs" is adopted for seated mobility devices in this paper. The risk of entrapment is exacerbated at skewed crossings, at crossings with uneven surfaces and where the top of the rail is higher than the adjacent surfacing [5,6]. Other mobility devices such as wheeled walkers, prams, walking frames and walking canes can also get trapped in the flange gap, creating the possibility of falls or increasing the time it takes the pedestrian to clear the crossing [2,3]. Flange gaps can also pose a risk to users of larger-wheeled vehicles such as bicycles, with this risk highest when bicycles cross at shallow angles to the tracks. Despite broad acknowledgement of the flange gap hazard, previous reviews of pedestrian crossing safety have noted a dearth of research in this area and highlighted the need for further investigation [5,6].

The focus of this paper is on the hazards posed to wheelchair users in Australia when crossing flange gaps, given their limited ability to free a trapped castor wheel. It has been estimated that there were approximately 640,000 Australians who regularly used mobility devices [8] of whom 190,000 are wheelchair users [9], and that the number of wheelchair users is predicted to increase as the population ages [5,6]. Given the number of wheelchair users and the risk of mishap, this is an important area for study. A number of studies [2,6,10] have investigated the opinions of pedestrians with disabilities, disability service providers, peak bodies and subject matter experts about the hazards at railway pedestrian crossings. The issues raised relating to the flange gap included that skewed or uneven pathways increased the risk of

CONTACT Carolyn A. Unsworth c.unsworth@federation.edu.au Institute of Health and Wellbeing, Federation University Australia, Building 5N- RM105| Gippsland Campus, PO Box 3191, Gippsland Mail Centre, Victoria 3841, Australia

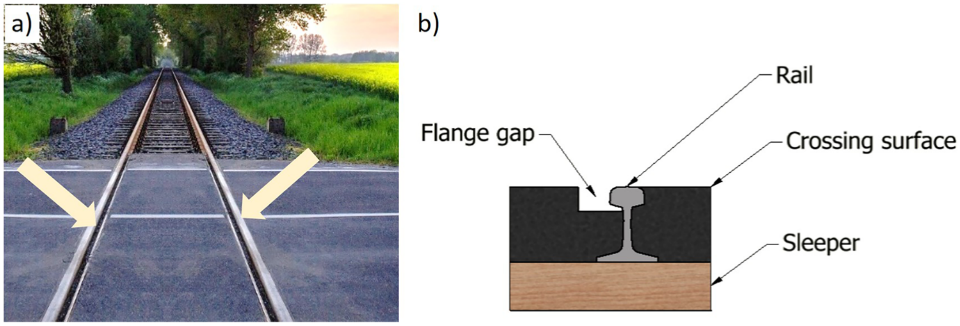


Figure 1. (a) Illustration of flange gaps at a railway crossing *(free image by Michael Treu from pixabay)* (b) cross-section showing a flange gap.

getting trapped. Wheelchair users noted that it can be necessary to pivot manual wheelchairs onto their back wheels to clear the rail and flange gap. This increases the risk of tipping the wheelchair and may result in the front castors, whilst being lifted clear of the ground, rotating away from the direction of travel, which increases the risk of entrapment in the flange gap if the castors are not clear of the flange gap when they are brought back down. Mobility scooter users noted that uneven surfaces can cause scooters to stall, stranding the pedestrian on the crossing. Traversing the crossings more slowly to avoid stalling increases the time to clear the crossing and hence the exposure to collision risk. Motorised wheelchair users reported losing control of wheelchairs on uneven crossing surfaces or having to drive wheelchairs at uncomfortably high speeds to clear a protruding rail head and/or the flange gap. Respondents also noted that if wheelchair castors become entrapped in the flange gap, they can be extremely difficult to free, particularly for motorised wheelchairs which can weigh over 150 kg. The need to change direction to avoid other pedestrians using the crossings was also noted to increase the risk of flange gap entrapment.

National rail safety statistical data in Australia reveal that 11 collisions with pedestrians on a level crossing and 1,505 near misses were recorded between July 2015 and December 2018 [11]. Other data sources recorded nine pedestrian fatalities on level crossings between July 2012 and July 2018 [12–15]. In the state of Victoria (population 6.68 million) between 1999 and 2002, 14 incidents involving wheelchairs were reported to the Victorian Safety and Technical Services branch of the Department of Infrastructure, including three fatalities due to a train striking a wheelchair user at a pedestrian crossing, with the flange gap a causal factor in at least one incident [6]. In New Zealand, between 2009 and 2019, 42 collisions with a person occurred at rail crossings, 23 of which were fatal, with one of these involving a wheelchair user. In the same period, 496 near misses were recorded, of which 14 involved mobility devices (5 wheelchairs, 2 walking frames, 1 walking stick, 3 mobility scooters, 1 infant's pushchair), with five of these involving mobility devices getting stuck on the crossing or in the ballast forming the bed and surrounds of the railway track (Based on Australian Level Crossings Assessment Model (ALCAM) data Jan 2010–Dec 2019 provided by Kiwi Rail in a personal communication, 1 March 2020). Other countries, including Canada [16,17], Japan [18], United Kingdom [19] and countries in Europe [20] have also reported rail crossing accidents or near misses, some of which involved pedestrians using mobility devices becoming immobilised and stuck, with some incidents leading to serious injury or death. From these reports, it was evident that the incidents in which the flange gap was reported to be the main cause or contributing factor all involved pedestrians who were using mobility devices.

Table 1. Description of 4 models of flange gap fillers.

Model	EpFlex Railseal Shallow Flangeway	Epflex Railseal Enclosed Flangeway	Sylomer Rail Groove Filler	veloStrail
Manufacturer	Polycorp	Polycorp	Getzner	Kraiburg Strail
Flangeway Type	Reduced	Closed	Closed	Closed

Australian Standard 1742.7:2016 Manual of uniform traffic control devices; Part 7: Railway Crossings [21], sets out the requirements for railway crossings in Australia. The maximum permitted flange gap width is 65 millimetres, maintained to a maximum of 75 mm. The maximum depth of a flange gap is 50 mm. A maximum change in level of 5 mm from the rail to the adjacent pavement is also specified. Pedestrian crossings are required to have skew angle of no less than 70° to the track, though a square crossing is preferred. An illustration of a flange gap at a crossing is provided in Figure 1.

Compressible fillers are the only commercially available method of reducing or eliminating the flange gap at pedestrian crossings. Four models of flange gap fillers are presented in Table 1. Of these systems, veloSTRAIL is the most widely adopted internationally. VeloSTRAIL is a full-rubber modular system which incorporates a removable compressible filler panel. Panels are held together using internal ties and the crossing can be fixed in position by tying back to the rails with end ties. Over time, the passage of train wheels wears a groove in the filler panel.

While the number of incidents involving wheelchair users is relatively small compared to the total number of incidents involving pedestrians, the impact can be catastrophic as any incident at pedestrian rail crossings has the potential to result in serious injury or death. Additionally, people using wheelchairs can have a heightened level of anxiety because of the need to negotiate rail crossings and the fear of entrapment. Given the paucity of research into this topic, the primary aim of this study was to investigate the risk of entrapment and ease of extraction of wheelchair castors in open or partially filled flange gaps by undertaking laboratory testing with research staff and wheelchair users. A secondary aim was to examine user experience of ride quality when traversing such flange gaps.

Methods

Laboratory study

Study design

A laboratory study was undertaken to investigate the interplay of factors affecting the risk of entrapment of wheelchairs in the flange gap, the ease of extraction of entrapped wheelchairs from the flange gap and the effect of fillers used to reduce the dimensions of the flange gap. Testing was conducted on a purpose-built timber test platform incorporating a single rail and a flange gap. The platform was designed so that the flange gap profile, surface friction and vertical rail misalignment could be varied, and so that the rail and flange gap could be crossed at different angles and speeds. Standard open flange gap profiles and reduced flange gap profiles were tested. Testing took place in the Faculty of Engineering, Computer and Mathematical Sciences at the University of Adelaide, between the 6 and 22 January 2020.

Study protocol

Four wheelchairs, hired from and set up by Independent Living Specialists, were tested: a manual wheelchair and three powered wheelchairs, which were selected to give a range of drive-wheel positions, castor widths and costs (Tables 2 and 3, and Figure 2). To minimise safety risks, this testing was undertaken by a laboratory technician seated in the wheelchair. The technician had no prior experience of operating a wheelchair.

Test parameters

Tests were conducted using the following range of parameters: flange gap widths (40, 65, 75, 85 mm); flange gap profiles (square, trapezoidal); vertical misalignment with the rail (0, 5, 10 mm); crossing angle (45, 60, 70, 90°); crossing speed (1.8, 5.0 km/h); and surface coefficient of friction (non-slip paint [$\mu \approx 0.43$], anti-slip self-adhesive tape [$\mu \approx 0.87$]). Figure 3 depicts the flange gap profiles used in testing.

Some important parameters were not included within the scope of testing. Firstly, due to space limitations and to simplify testing, only one rail was incorporated into the test platform. Secondly, the effect of surface unevenness was not tested because the unlimited range of possible surface profiles meant that testing this parameter was impractical. Thirdly, entrapment testing was limited to a straight path across the flange gap, albeit at different skew angles, even though it is acknowledged that entrapment may occur if the wheelchair user adjusts or reverses the wheelchair's direction of motion near the flange gap. Finally, for ease of construction and cost, the reduced flange gap profiles were formed using timber inserts. In reality, a compressible filler would be used but it was deemed unlikely that the material type would significantly affect the results.

The test platform is shown in Figure 4. The platform was offset on both sides of the rail to allow the flange gap to be crossed on the skew. The crossing angles were delineated using tape. The surfaces of the plyboard adjacent to the flange gap and rail were coated with Berger non-slip paint for low-friction tests and Floorsafe anti-slip self-adhesive tape for high-friction testing. Shims at each end of the rail were used to adjust the vertical misalignment of the rail. The flange gap profile was adjusted using prefabricated inserts made from wood (Figure 3).

Entrapment tests. Two types of tests were undertaken. The first type, entrapment testing, determined the risk of wheelchair castors becoming trapped at various crossing angles over a range of flange gap widths and vertical rail misalignments when the crossing is traversed with a straight path (no change in direction on the crossing). Entrapment testing was undertaken in a standardised fashion:

1. The appropriate insert was fixed in the flange gap and the rail shimmed to the required level.
2. The rail was crossed in the forward direction from the field side at 90° at low speed in the manual wheelchair.
3. The wheelchair was reversed back over the rail at the same angle.
4. Steps 2 and 3 were repeated three times.
5. Steps 2 to 4 were repeated at high speed.
6. Steps 2 to 5 were repeated at 70° and 60°.
7. Steps 2 to 4 were repeated at 45° (low speed only).
8. The number of times the wheelchair became trapped was recorded.

Table 2. Details of the wheelchairs included in the laboratory testing.

Chair Type	Manual	Rear-wheel drive	Front wheel drive	Mid-wheel drive
Manufacturer	Sunrise Medical	Royale Medical	Permobil	Sunrise Medical
Model	Breezy Basix[2]	Travel Lite	C300	QM-710
Mass (kg)	16.4	30.8	151.2	165.4
Approximate value new (AU$)	$500	$3,000	$28,000–36,000	$25,000–33,000

Table 3. Wheelchair wheel dimensions.

	Breezy Basix2 (manual wheelchair)	Travel Lite (rear-wheel drive)	C300 (front-wheel drive)	QM-710 (mid-wheel drive)
FC-x (mm)	374	430	–	330
RC-x (mm)	–	–	624	434
D-y (mm)	585	543	540	565
FC-y (mm)	545	480	–	555
RC-y (mm)	–	–	367	407
D-dia (mm)	588	325	334	340
FC-dia (mm)	200	190	–	150
RC-dia (mm)	–	–	200	150
D-thk max (mm)	24	55	67	73
D-thk tread (mm)	24	48	63	73
FC-thk max (mm)	31	50	–	46
FC-thk tread (mm)	22	33	–	46
RC-thk max (mm)	–	–	64	46
RC-thk tread (mm)	–	–	Rounded profile	46
FC-tr (mm)	56	42	–	47
RC-tr (mm)	–	–	59	47

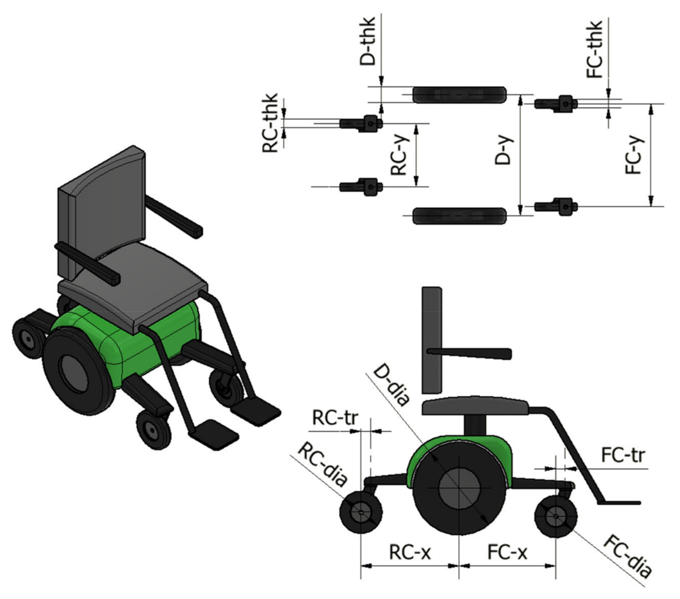


Figure 2. Wheelchair wheel notations for dimensions in Table 3 (the illustration here showing a mid-drive wheelchair).

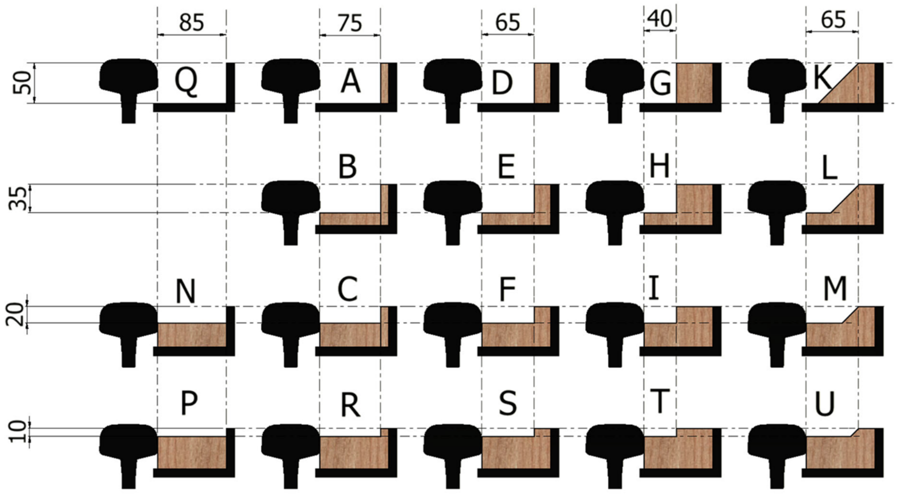


Figure 3. Illustrations of 19 profiles of wooden inserts used to vary the residual flange gap dimensions both horizontally and vertically.

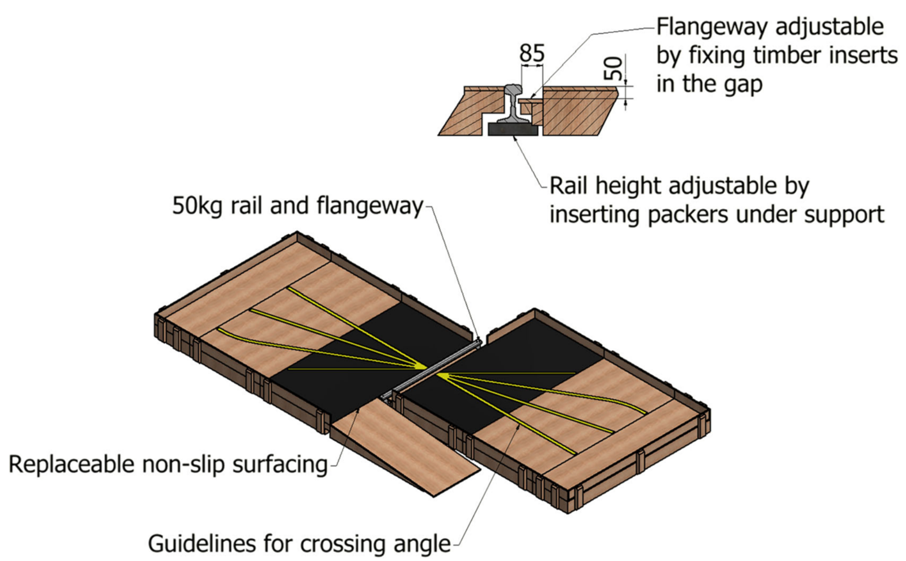


Figure 4. Test platform used for entrapment and extraction testing.

9. Steps 2 to 8 were repeated from the gauge side of the rail.
10. Steps 2 to 9 were repeated for the rear-drive, front-drive and mid-drive wheelchairs.

The surface friction was considered unlikely to affect entrapment testing. Therefore, testing was only undertaken with the low-friction surface. Only full-depth profiles Q, A, D, G and K were included in testing.

The wheelchair was considered to be trapped if motion in the intended direction was arrested. Whether it was possible to free the wheelchair, for example by changing direction, had no bearing on the recorded result. The intent of this approach was to provide a clear delineation between a pass or fail outcome for entrapment.

Extraction tests. The second testing type of testing, extraction testing, determined if the wheelchair castors could be extracted from the flange gap, without external assistance, after the castors had been placed in the flange gap. For the extraction testing, the wheelchair castors were placed in the gap and a record made of whether the castors could be removed from the flange gap. Such testing was considered necessary irrespective of the results of entrapment testing because even if no entrapments occurred driving in a straight line across the rails on the square or on the skew, it is still possible for wheelchair castors to become trapped if the direction of motion of the wheelchair is changed when the castors are close to the flange gap.

The castors were placed in the flange gap in various orientations, the wheelchairs were then attempted to be driven forwards or backwards, and a record made of whether the castors could be extracted from the flange gap. It is possible that an entrapped castor, unable to be extracted by a forwards-backwards motion, may have been freed by rocking or rotating the wheelchair or by the operator shifting their body weight. However, users with limited mobility may not be able to shift their body weight and, in an urgent situation of entrapment on a level crossing, it is not reasonable to expect that an operator would be able to, or have time to, try multiple combinations of movements to free the chair. The high-speed drive setting was used for extraction testing of the powered wheelchairs. To limit the extent of testing, it was assumed that if the castors could be extracted on the low friction surfacing for a given profile and rail misalignment, then they could also be extracted on high friction surfacing, and if no castors could be extracted for a given flange gap profile and vertical rail misalignment, then it also would not be possible to extract the castors for the same profile with a greater vertical rail misalignment.

Extraction testing was undertaken in a standardised fashion:

1. The appropriate insert was fixed in the flange gap and the rail was shimmed to the required level.
2. The wheelchair castors were placed in the flange gap, trailing in the same direction with the drive wheels on the field side of the rail.
3. The wheelchair was driven straight forward, and it was recorded whether the castors were freed from the flange gap.
4. Steps 2 and 3 were repeated while driving the wheelchair straight backwards.
5. If the wheelchair could be freed either driving forward or backward, Steps 2 to 4 were repeated first with the castors facing inward and then with the castors facing outward.
6. Steps 2 to 5 were repeated from the gauge side of the rail.
7. Steps 2 to 6 were repeated for each wheelchair.
8. For the mid-drive wheelchair, Steps 2 to 6 were repeated for the second set of castors.

Extraction testing results were categorised as "cannot trap" when the castor was too wide to become trapped in the flange gap, "free forward" when the castor could be freed by driving the wheelchair forwards, "only free backwards" when the castors could not be freed by driving the wheelchair forwards but could be freed by driving the wheelchair backwards, and "cannot free" when it was not possible to free the castors by driving forwards or backwards.

Wheelchair user extraction and ride quality trials

Study design

To improve the generalisability of the laboratory-based study, similar tests to those conducted by the research team were conducted with wheelchair users. In addition to the wood filler profiles used in the laboratory testing, the most commonly used commercial flange gap filler, veloSTRAIL, was also included in the testing with wheelchair users so as to assess the effect of wear of this profile on the risk of entrapment. Finally, information was gathered from the wheelchair users on the ride quality over the partially filled flangeway. Ethical approval for this component of the broader study was granted by the Human Research Ethics Committee, University of Adelaide H-2021-039.

Participants

Wheelchair users were recruited in Adelaide, South Australia, through advertisements placed with advocacy groups and local disability service providers. Potential participants were provided with an information sheet and, if willing to participate, provided informed consent.

Study protocol

The test platform used in the wheelchair users' trials is shown in Figure 5. The platform incorporated two rails, both of which were positioned 5 mm above the adjacent surfacing, the maximum allowed by the Australian code. Adjacent to one rail, the surface was painted with a high-friction coating. The plyboard adjacent to the other rail was untreated. This provided surfaces with coefficients of friction higher and lower than would typically be the case for an asphalt or concrete crossing. Adjacent to each rail, a 50 mm deep and 85 mm wide groove was formed, in which inserts, similar to those used in the laboratory testing, could be fixed.

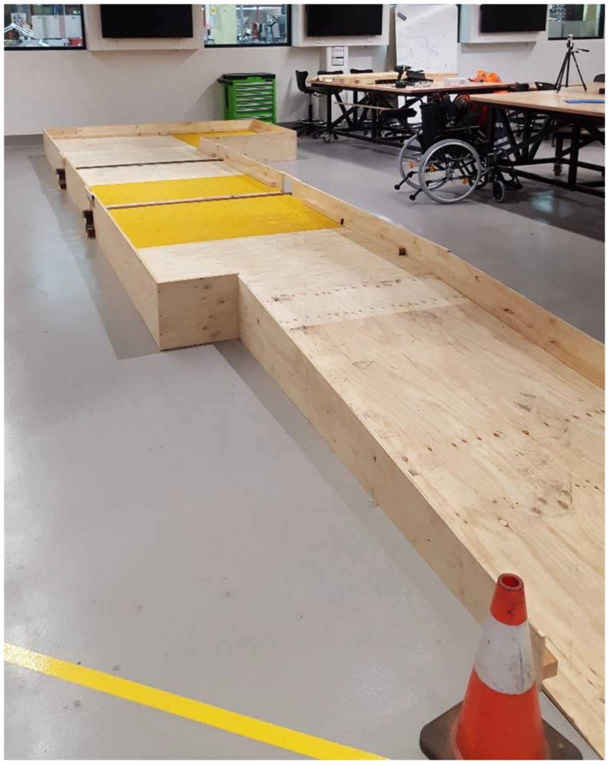


Figure 5. Platform used in wheelchair users' trials.

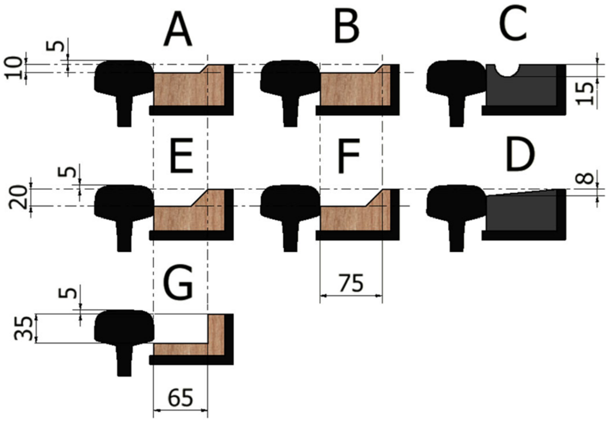


Figure 6. Similar to Figure 3 for the laboratory trials, this figure shows the flange gap profiles used in wheelchair users' trials. In this figure, C denotes worn and D denotes new veloSTRAIL gap fillers.

Five timber profiles were tested to simulate various flange gap profiles. As shown in Figure 6, these profiles are denoted A, B, E, F and G. In addition, worn and new veloSTRAIL filler panels were tested and denoted C and D respectively.

The trials were undertaken as follows:

1. The first profile was fixed in the groove adjacent to each track.
2. The participant traversed the rails in both directions several times and provided a qualitative rating of the ride quality.

3. On the low friction side of the rig, with the drive wheels on the gauge side of the rail, the wheelchair castors were placed in the gap and the participant was asked to try to remove them. It was recorded if the castors could be extracted on the first attempt, if it took multiple attempts to extract the castors, or if the castors were stuck.
4. Step 3 was repeated with the drive wheels on the field side of the same rail.
5. If wheel slip resulted in the participant being unable to extract the castor(s), steps 3 and 4 were repeated on the high friction side of the rig.

The tests were undertaken with the participants in groups of two to four. The duration of the trial for each group was limited to 2 h, which reduced the number of profiles which could be tested at any one time. With the first group of four participants, profiles A, B, C, D and G were tested. For all subsequent groups, profiles A, B, C, D, E and F were tested.

The participants then assessed ride quality on a Likert-type scale from 1 to 7 for which 7 indicated "good" ride quality, 5 "acceptable", 3 "unacceptable", and 1 "bad".

Results

Laboratory study

Entrapment tests

Under the procedure followed for entrapment testing, none of the wheelchairs became entrapped for a crossing angle of 60° or more. Figure 7 shows the overall entrapment count by wheelchair type, vertical rail misalignment and flange gap width for a crossing angle of 45 degrees. Typical modes of entrapment are shown and described in Figure 8. None of the entrapments involved both castors becoming

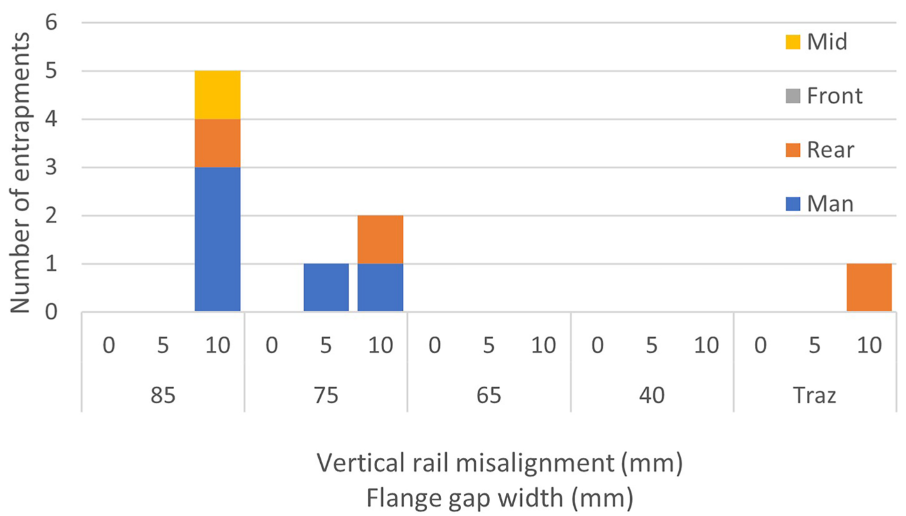


Figure 7. Number of entrapments for each wheelchair, by type, with rail misalignment and flange gap width for a crossing angle of 45° (no entrapments occurred for larger crossing angles). Traz denotes trapezoidal profile 'K' in Figure 3.

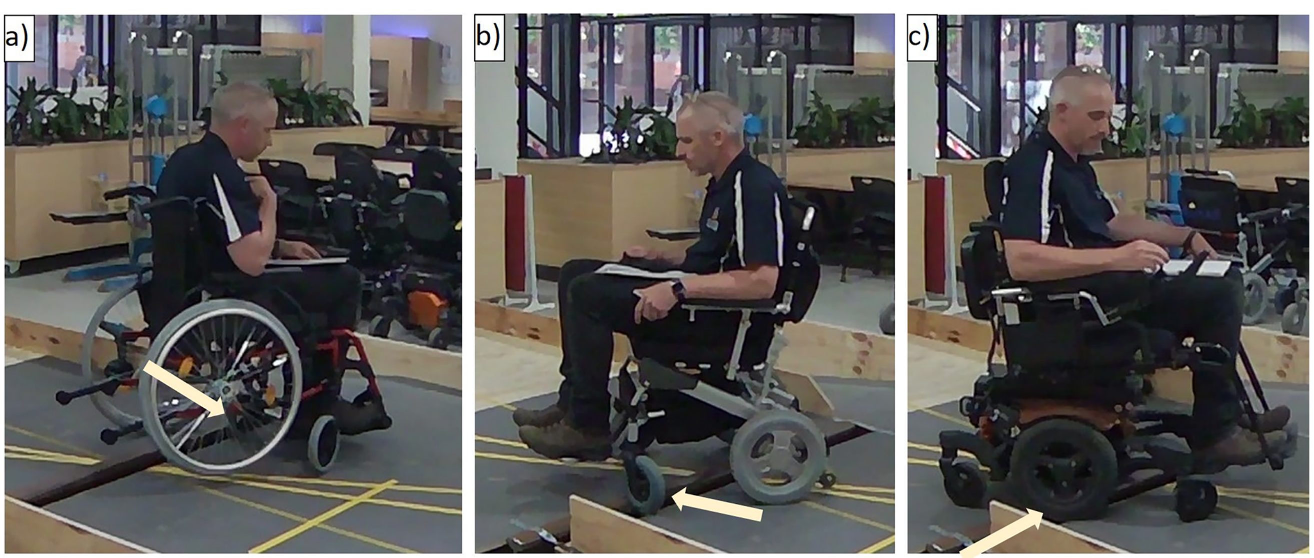


Figure 8. Illustrations of typical modes of entrapment for crossings at 45°: (a) the second castor of manual wheelchair to cross the rail tended to drop into the flange gap if care was not taken to drive rear wheels together. (b) the second castor of rear-drive wheelchair to cross the rail tended to slide along the rail preventing movement in intended direction. (c) when driving the mid-drive wheelchair backwards, one drive wheel and one castor settled in the flange gap and stalled the wheelchair.

trapped in the flange gap and in all cases the wheelchair could be easily extracted without external assistance. However, on several occasions when manoeuvring the wheelchair on the platform in preparation for testing, two castors dropped into the flange gap. This occurred either when the direction of motion was reversed just after the castors had crossed over the flange gap, or if the wheelchair was driven to cause rotation of the device close to the flange gap.

Extraction tests

Figure 9 shows the extraction rates by wheelchair type determined using the procedure described in Section 2.1.3.2. These results are presented as percentages to adjust for the fact that the mid-drive wheelchair, having two sets of castors, was subject to twice as many tests as the other chairs. As can be seen, the front- and mid-drive wheelchairs performed better than the manual and rear-drive wheelchairs. The difference in performance was, in large part, because the front- and mid-drive castors could not be trapped

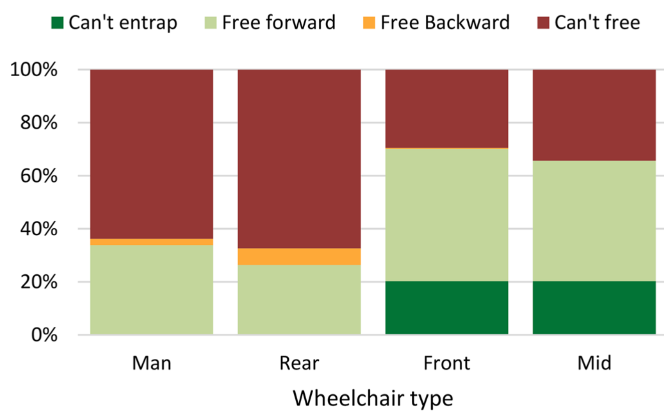


Figure 9. Extraction rates for the four wheelchairs.

in the 40 mm wide flange gap profile since the width of the castors exceeded 40 mm. However, even if 40 mm wide profiles are excluded, the front- and mid-drive wheelchairs performed better.

A breakdown of extraction rates from the various profiles is provided in Figure 10. A key to this graphic is provided in Figure 11. It was not possible to extract the castors of any wheelchairs from the standard flange gaps (65 mm or 75 mm wide and 50 mm deep). For all flange gap widths, including the trapezoidal profiles, reducing the flange gap depth from 50 mm to 35 mm did not considerably affect the results. Only after the flange gap depth was reduced to 20 mm was there a noticeable difference in the extraction count. The depth of the flange gap had to be reduced to 10 mm to ensure that all wheelchairs could be extracted.

For a depth of 20 mm, reducing the width of the flange gap increased the entrapment count. It was observed that this was because for the castor to lift out of the flange gap, the castor needed to be able to rotate to bring the circumference of the tyre into contact with the edge of the flange gap and so provide the upward component to the reaction force necessary to lift the castor out of the gap. A narrow gap constrained rotation and trapped the castor. The trapezoidal profile (Traz) was considered to be a more durable profile for a filler which partially filled the gap. The extraction count for the trapezoidal profile was similar to that for a 40 mm wide gap.

Wheelchair user tests

Participants

Twelve participants were recruited, eight of whom used manual wheelchairs and all of whom were experienced wheelchair users of 5+ years (see Table 4). Seven of the eight manual wheelchairs had small castors with diameters between 105 and 125 mm and the other had a front castor diameter of 200 mm. The castor thickness for the manual wheelchairs was between 35 and 48 mm. The remaining four participants used mid-wheel drive wheelchairs,

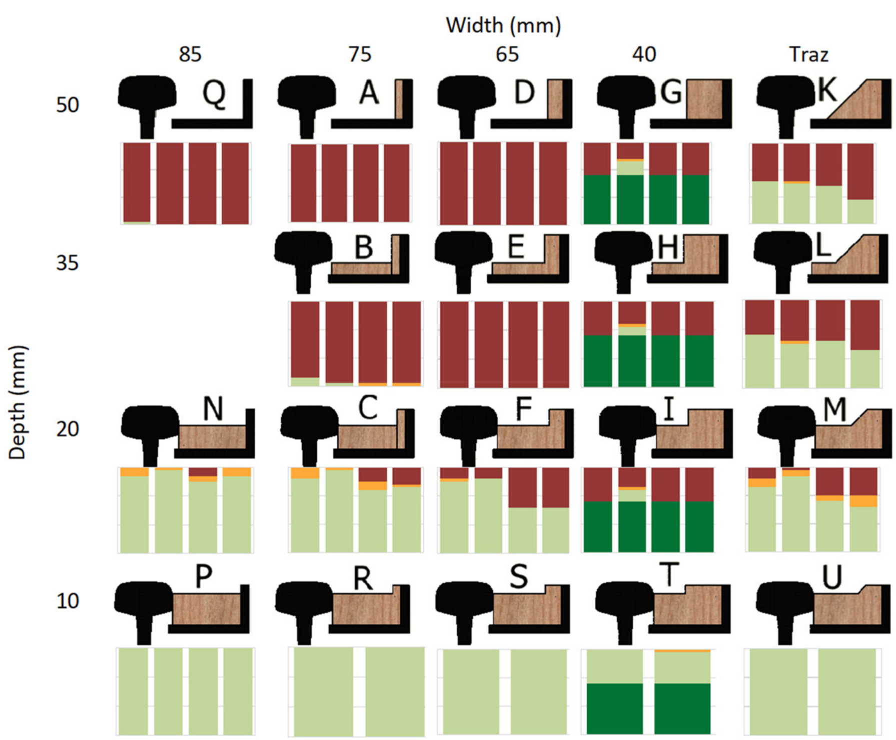


Figure 10. Extraction rates from different profiles. Profiles R, S, T and U were tested with a vertical rail misalignment of 5 mm only. Dark green = Can't entrap, Light green = Free forward, Yellow = only free backward, Red = Can't free.

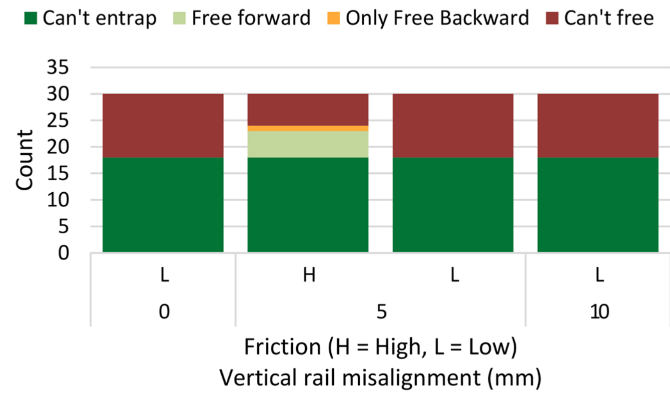


Figure 11. Key to Figure 10 using profile G as an example.

Table 4. Participant and wheelchair characteristics. For mid-drive chairs, front and rear castors had the same dimensions unless noted otherwise.

Participant (Gender)	Type of wheelchair (castor diameter/ thickness in mm)	Participant (Gender)	Type of wheelchair (castor diameter/thickness in mm)
1. (F)	Manual (200/48)	7.(F)	Mid-wheel drive (144/48)
2. (F)	Manual (125/36)	8.(F)	Manual (122.5/36.6)
3. (F)	Manual (122/35.8)	9. (M)	Manual (125/36)
4. (F)	Mid-wheel drive (140/48)	10.(M)	Manual (105/36.8)
5. (M)	Manual (120/35)	11.(M)	Mid-wheel drive (140/50)
6. (F)	Manual (125/36)	8.(F)	Mid-wheel drive (Front 127/45 Rear 145/48)

with castor diameters ranging from 127 to 145 mm and castor thickness of 45 to 50 mm.

Ability to free castors from the flange gap

The results of participant ability to extract castors from the flange gap are summarised in Table 5. Most participants were able to free their castors with one try, with the exception being profile G (Figure 6) from which two of the four participants in this first group of participants were unable to free their castors. The two veloSTRAILs profiles (C [worn], D [new]) performed particularly well, with five and 12 participants, respectively, unable to be trapped, and the remaining participants able to free the castors on the first try.

Ride quality

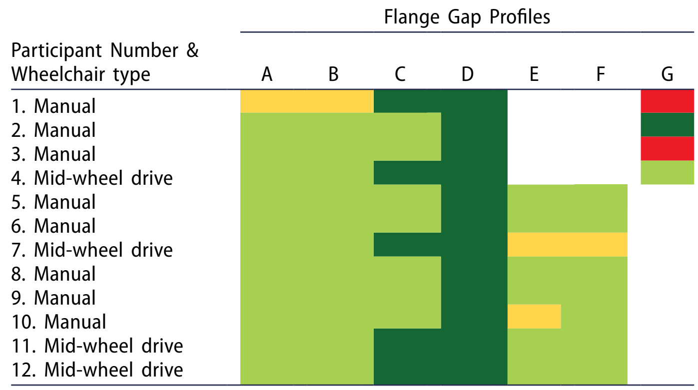
The average scores for ride quality are shown in Table 6. Only the 10 mm deep, 65 mm wide profile, and both the new and worn veloSTRAIL profiles were deemed to provide an acceptable or good ride quality. The worn veloSTRAIL profile scored higher overall than the new profile.

Discussion

This study investigated the risk of entrapment of wheelchair castors in the flange gap, and possible mitigation measures, by undertaking laboratory entrapment and extraction testing involving four wheelchairs used by a technician and additional testing on entrapment, extraction, and ride quality with 12 wheelchair users. In the laboratory testing, only nine entrapments were recorded in standard flange gaps and in all nine cases the test parameters were outside the limits imposed by the relevant Australian Standard AS 1742.7 [21]. In other words, when testing flange gaps that met Australian Standards, no wheelchairs were entrapped. However, this entrapment testing did not consider the possibility of the user changing direction when the wheelchair castors were in the vicinity of the flange gaps, for example to avoid another pedestrian, due to uneven surfacing, or if it is decided there is insufficient time to complete a crossing. Therefore, extraction testing was also undertaken whereby the wheelchair castors were placed in the flange gap, and it was determined whether the castors could be extracted without external assistance. For all wheelchairs tested, it was not possible to extract the castors from an Australian Standard compliant, flange gap. The use of a compressible material to fill the flange gap such as veloSTRAIL as used in this study would eliminate the risk of entrapment. However, such fillers can increase maintenance requirements due to wear, or strip lubricating grease from the wheels. Therefore, partially filling the gap might be preferable. However, extraction testing demonstrated that the castors of all wheelchairs could be extracted only if the depth of the flange gap was reduced to 10 mm.

From the trials involving wheelchair users, all participants were able to free their castors from flange gaps which were 10 mm or 20 mm deep, suggesting that the laboratory testing by the technician was overly conservative. However, the participants indicated that reducing the flange gap depth to a depth of 10 mm and width of 65 mm was necessary to provide an acceptable ride quality. The two veloSTRAILs profiles (new and worn) performed well in the wheelchair user trials, with all users either being unable to be trapped (since the worn groove was narrower than the

Table 5. Summary of results for participants' ability to extract castors from the flange gap for the different flange gap profiles.



Key: dark green = did not trap castors, light green = freed first try, yellow = more than one try to free, red = could not free castors, blank = not tested.

Table 6. Summary Of ride quality ratings from 12 participants for flange gap profiles a to G.

Profile	Depth (mm)	Width (mm)	Average Score 1-Bad to 7-Good	Equivalent Assessment
A	10	65	4.3	Acceptable
B	10	75	3.5	Unacceptable
C	Worn veloSTRAIL profile		6.2	Good
D	New veloSTRAIL profile		5.2	Acceptable
E	20	65	3.5	Unacceptable
F	20	75	3.6	Unacceptable
G	35	–	1.5	Bad

castor width) or being able to extract their wheelchair easily. The ride quality of the new veloSTRAIL profile was judged to be acceptable and the worn profile to be good. It was unusual that the worn veloSTRAIL profile scored higher overall than the new profile. As can be seen from Figure 6, the worn profile had deformed to reduce the step to the rail compared to a newly installed profile, which improved ride quality. The wear profile will depend on the lateral wheel flange position over the crossing. It is not necessarily the case that all worn profiles will improve ride quality.

Implications for policy makers and practitioners

The laboratory trials indicated that, when a wheelchair user traverses a crossing that is compliant with the Australian Standard using a straight path, the risk of entrapment is low. Therefore, Australian guidelines on flange gap width and vertical rail misalignment are appropriate but should be strictly adhered to, and upgrades to non-compliant crossings should be prioritised. However, even on crossings that meet the Australian Standard, the need to avoid obstacles or turn back after starting to cross may result in castor entrapment.

The laboratory testing demonstrated that if both wheelchair castors dropped into a standard flange gap, they could not be removed. Therefore, when selecting flange gap fillers, railway operators should consider reducing the depth of the gap to <20 mm to reduce entrapment risk, or to <10 mm (which in practical terms equates to no gap) to eliminate entrapment and provide an acceptable ride quality. Our findings could also be used to update international guidelines. For example, it is suggested that the current Design Guidance for Pedestrian and Cycle Rail Crossings in New Zealand [4], recommending the use of a flange gap filler for skew angles < 70° and strongly recommending them for skew crossings < 60°, should be reworded to *require* compressible fillers for skew angles ≤ 70°. Furthermore, as it is possible for a wheelchair castor to become trapped in a standard flange gap, even for square crossings, a requirement to install a filler for skew angles < 70° should not preclude their use on crossings with higher skew angles or on square crossings.

Until all crossings can be upgraded, and even thereafter, it is critical that signage warning wheelchair users about the flange gap hazard is provided. Such signage warning might help raise awareness of this issue among wheelchair and walking frame users and encourage additional care. For example, signage could illustrate the risk of a wheel getting stuck in the gap, and provide the emergency assist phone number. Improved signage, with contact details and a crossing identification number, would also enable crossing users to report near-misses or crossing defects more easily.

As well as signage to reduce risk, there is other relevant information which cannot be succinctly presented in crossing signage that should be incorporated into wheelchair user manuals and training by relevant health care professionals such as occupational therapists. For example, from our laboratory testing, it appeared that driving in a straight line across the crossing, on the skew, is safest for the range of skew angles allowed by current standards (approximately 60–120 degrees). In contrast, manoeuvring the wheelchair to cross each rail on the square may increase the risk of entrapment. The exception to this was that users of manual wheelchairs, which have small castors (105–125 mm diameter), need to cross on the square, lifting the castors off the ground to clear the flange gap. This information could be directly included into training materials with illustrations of the skew crossing strategy, and include these specific details for power wheelchair users, scooter users as well as manual wheelchair users. Wheelchair manuals and training guides should also include advice that, if a wheelchair becomes entrapped in a flange gap, it is recommended, given the weight of some powered wheelchairs, that the best option for assistance would be to remove the wheelchair user to a safe position, and only try to retrieve the wheelchair when it is safe to do so, though this would only be effective if the user were able to communicate this to those providing assistance in an emergency situation. Our research has revealed that once trapped, it is extremely difficult to free an occupied wheelchair, therefore instruction manuals should prepare the wheelchair users that in an emergency they need to use their preferred evacuation method to get themselves, or be evacuated, off the crossing. Most wheelchair users have planned and tested emergency procedures, however, wheelchair instruction manuals could provide details for managing castor wheel entrapment at level crossings. Depending on whether other people are around, lighting and visibility, as well as the wheelchair user's personal characteristics such as upper body strength, guiding information could include instructions for coming out of the chair to ground level and rolling or dragging themselves off the crossing. Or if other people are around, wheelchair users can call to raise the alarm, and be carried off the crossing before an assistant return to remove the unoccupied wheelchair from the tracks when it is safe to do so. Illustrations could be provided in training manuals to demonstrate such events. Emergency strategies to suit individual circumstances and types of wheelchairs can be developed with experts in this area such as occupational therapists.

Limitations

Several limitations reduce the generalisability of this work. In future, real-world testing is required which includes people using rear-wheel drive wheelchairs. It may also be important to consider wheelchair user' personal profiles such as height and weight and their associated centre of gravity to determine if an individual's profile promotes entrapment. Only one rail was incorporated into the test platform for the laboratory testing, the effect of surface unevenness was not tested, entrapment testing was limited to a straight path across the flange gap, and the reduced flange gap profiles were formed using timber inserts whereas, in reality, a compressible filler would be used. Each of these limitations is considered in turn. While ideally, testing should have occurred with two rails and flange gaps to mimic reality, in essence each rail is sufficiently far apart that each flange gap crossing event occurs in isolation. However, further testing with two rails could be useful to examine if there is an effect for fatigue, particularly for manual wheelchair users who need to propel their wheelchairs over the gaps. Surface unevenness around the flange gaps should also be varied in future studies. While the laboratory surface was smooth, rough and/or uneven bitumen or other surfaces surrounding the flange gap could promote entrapment, irrespective of the gap and angle of crossing. Multiple testing paths could be used in future studies to ensure comprehensive understanding of the effect of irregular versus straight crossing, perhaps by placing an obstacle for the users to avoid. Finally, for the laboratory trial, only timber inserts were used. It was assumed that these inserts adequately mimic a compressible filler since they are designed to compress under the passing train wheel flanges, not under loads imposed by mobility devices. However, the assumption could be confirmed by further testing using a range of rubberised compressible fillers.

Directions for future research

Further research to replicate and extend these findings in real world settings to enhance ecological validity is required. For example, the laboratory tests reported in this study need to also be conducted at level crossings to determine the real-world consequences of the insertion of different gap fillers, and outcomes for people using their wheelchairs and crossing at differing angles. In addition, the most widely available commercial flange gap filler, veloSTRAIL, was included in the testing with 12 participants to assess entrapment, ride quality and the effects of wear of this profile on the risk of entrapment and ride quality. This material, and other commercially available fillers should also be included in laboratory-based and real-world tests in the future. None of the volunteers used rear-wheel drive wheelchairs, and these should also be tested in the future. Finally, user age, weight and functional status demographic data should be collected in the future to better contextualise findings.

Conclusion

The laboratory study and wheelchair user tests both demonstrated that the risk of entrapment of wheelchair castors in a flange gap is low if a crossing compliant with Australian standards is traversed in a straight line at an angle of 60° or more to the tracks. However, a wheelchair user may have to change direction while crossing to avoid another pedestrian, due to a rough surface, or when negotiating a skewed crossing square to the rails. The risk of a castor becoming trapped in such circumstances is significant and the use of gap fillers is necessary to reduce this risk. Policy makers and practitioners can use the following findings to improve safe wheelchair passage over flange gaps: (i) Australian guidelines on flange gap width and vertical rail misalignment reduce risk and should be strictly adhered to; (ii) upgrades to non-compliant crossings should be prioritised, (iii) when selecting flange gap fillers, railway operators should consider reducing the depth of the gap to < 20 mm to reduce entrapment, or to <10 mm to eliminate entrapment and provide an acceptable ride quality, (iv) education and instructions for wheelchair users should include information on traversing flange gaps at angles between 60 and 120 degrees, (v) wheelchair users should have practiced an emergency strategy in the event that a castor wheel become trapped in a flange gap, and (vi) signage on risk of flange gap entrapment and emergency procedures should be installed at all crossing points. Further research is required to confirm these findings and further examine the performance of a wide range of filler materials to reduce the risk of entrapment using larger samples of wheelchair users. Ride quality remains a concern, and additional investigations that aim to identify both the safest and smoothest approach to crossing flange gaps is also required.

Acknowledgements

The contribution of the participants to test the flange gaps is gratefully acknowledged. We would also like to thank Independent Living Specialists Australia for their assistance in supplying and setting up the wheelchairs; Kiwi Rail for providing extensive data which informed the study; ARTC for providing the rails for testing; Phoenix AG for providing the new and worn veloSTRAIL fillers; and Gary Bowman of the Technical Services and Infrastructure Team at The University of Adelaide for has assistance in constructing the test platforms.

Author contributions

KF, MB and JT conceived the study. KF collected all data with support from MB, JT and CU. All authors were involved in drafting and reviewing the manuscript.

Disclosure statement

None. In order to test the veloSTRAIL product, the supplier, Phoenix AG (Aust) Pty Ltd provided their insert and technical specification details. The authors do not have any association with Phoenix AG (Aust).

Funding

This study was funded by the Australasian Centre for Rail Innovation, Project LC15B.

ORCID

Carolyn A. Unsworth http://orcid.org/0000-0001-6430-2823

References

[1] CTC, Campbell Technology Corporation. 2012. Meeting the needs of all users: accessibility issues at grade crossings. in Institute of Transportation Engineers Annual Meeting. 2012. Atlanta, Georgia.

[2] Delmonte E, Tong S. 2011 Improving safety and accessibility at level crossings for disabled pedestrians. London, UK: Rail Safety and Standards Board. https://www.rssb.co.uk/research-catalogue/CatalogueItem/T650.

[3] Fitzpatrick K, Warner J, Brewer MA, et al. 2015. Guidebook on pedestrian crossings of public transit rail services. Washington, DC: Transportation Research Board: https://www.worldtransitresearch.info/research/5593/.

[4] KiwiRail. 2017. VlaStrada Ltd and Stantec Ltd, Rail Crossing Pedestrian/Cycle Design GuidanceKiwiRail; [cited 2023 Mar 8]. Available from: https://www.kiwirail.co.nz/assets/Uploads/documents/4eea8a615d/RailXing-PedBikeXingDesign-RevisedGuide.pdf.

[5] TRB. 2007. Transportation Research Board. Wheelchairs Crossing Flangeway Gaps at Railway Crossings; [cited 2022 Aug 17]. Available from: https://rns.trb.org/details/dproject.aspx?n=13462.

[6] VDI. 2002. Victoria Department of Infrastructure. Wheelchair Safety at Rail Level Crossings Taskforce. Summary report to the Minister for Transport; [cited 2022 Aug 17]. Available from: https://www.vgls.vic.gov.au/client/en_AU/vgls/search/detailnonmodal/ent:$002f$002fSD_ILS$002f0$002fSD_ILS:538556/ada?qu=Transport+safety.&d=ent%3A//SD_ILS/0/SD_ILS%3A538556%7EILS%7E74&ps=300&h=8.

[7] KiwiRail. 2013. Summary of KiwiRail's Report into Morningside Accident; [cited 2023 Mar 8]. Available from: https://at.govt.nz/media/291470/morningside-accident-report.pdf.

[8] ABS, Australian Bureau of Statistics. 2015. Use of aids and equipment by people with a disability in Australia; [cited 2023 Mar 8]. Available from: https://www.abs.gov.au/ausstats/abs@.nsf/Lookup/4430.0main+features202015#:~:text=Consistent%20with%20the%202012%20SDAC,%25)%20of%20those%20with%20disability.

[9] Disability Statistics. 2019. Australian Network on Disability. Disability Statistics; [cited 2023 Mar 8]. Available from: https://www.and.org.au/resources/disability-statistics/.

[10] MobilityBasics. 2019. Wheelchair Castors; [cited 2023 Mar 8]. Available from: https://mobilitybasics.ca/wheelchairs/casters.

[11] ONSR. 2019. Office of the National Safety Regulator, Annual Safety Report, 2018 to 2019; [cited 2023 Mar 8]. Available from: https://nraspricms01.blob.core.windows.net/assets/documents/Publication/ONRSR-2018-2019-Annual-Report-web-version.pdf.

[12] ONSR. 2013. Office of the National Safety Regulator, Annual Safety Report, 2012 to 2013; [cited 2023 Mar 8]. Available from: https://nraspricms01.blob.core.windows.net/assets/documents/Publication/NRSR017-Annual-Safety-Report-FA-web.pdf.

[13] ONSR. 2014. Office of the National Safety Regulator, Annual Safety Report, 2013 to 2014; [cited 2023 Mar 8]. Available from: https://nraspricms01.blob.core.windows.net/assets/documents/Publication/J004064-Annual-Safety-Report-2014_WEB.pdf.

[14] ONSR. 2015. Office of the National Safety Regulator, Annual Safety Report, 2014 to 2015; [cited 2023 Mar 8]. Available from: https://nraspricms01.blob.core.windows.net/assets/documents/Publication/Annual-Report-2014-2015.pdf.

[15] ONSR, 2017. Office of the National Safety Regulator, Annual Safety Report, 2016 to 2017; [cited 2023 Mar 8]. Available from: https://nraspricms01.blob.core.windows.net/assets/documents/Publication/ONRSR-Annual-Report-2016-2017-digital.pdf.

[16] TSBC. 2016, Transport Safety Board of Canada, Railway investigation report R16M0026; [cited 2023 Mar 8]. Available from: http://www.tsb.gc.ca/eng/rapports-reports/rail/2016/r16m0026/r16m0026.pdf.

[17] TSBC.,2019. Transport Safety Board of Canada. Rail Occurrence Database System. [CSV]; [cited 2023 Mar 8]. Available from: https://www.bst-tsb.gc.ca/eng/stats/rail/index.html.

[18] Japan Today. 2018. 5 fatal accidents involving electric wheelchairs stuck on rail crossings reported this year, in Japan Today; [cited 2023 Mar 8]. Available from: https://japantoday.com/category/national/5-fatal-accidents-involving-electric-wheelchairs-stuck-on-rail-crossings-reported-this-year.

[19] ORR. 2021. Office of Rail and Road. Rail safety; [cited 2023 Mar 8]. Available from: https://dataportal.orr.gov.uk/statistics/health- and-safety/rail-safety/.

[20] Eurostat. 2019. Rail accidents by type of accident (ERA data); [cited 2023 Mar 8]. Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Railway_safety_statistics_in_the_EU.

[21] Standards Australia. As 1742.7:2016 manual of uniform traffic control devices; part 7: railway crossings. 2016: Syndey, NSW: Standards Australia.