Australasian Transport Research Forum 2025 Proceedings
18-21 November, Auckland, New Zealand
Publication website: https://australasiantransportresearchforum.org.au/

Tram stop safety: Implications of Vision Zero and the Safe System framework

James Reynolds[1], Graham Currie[1]

[1] Public Transport Research Group, Monash Institute of Transport Studies, Department of Civil Engineering, Monash University

Email for correspondence (presenting author): julianjamesreynolds@gmail.com

Abstract

Vision Zero and the Safe System framework shift the focus in road safety towards virtually eliminating severe and fatal crash outcomes. They also emphasise that road managers and designers have the primary responsibility for safety, and that road systems need to be forgiving of (the inevitable) human errors. This contrasts to previous approaches, which focused more on reducing overall risk often through reducing crash likelihood, and the widespread use of encouragement, enforcement and education programs to change road user behaviour. Much research has already examined safety at tram stops, especially in Melbourne and including at: kerbside; safety zone; easy-access (raised-hump); and platform stops. Various studies have: used a road safety auditing approach; examined crash data; and/or developed sophisticated statistical models to improve understandings of the factors involved in or explaining crash likelihood. However, much of this research pre-dates the wider adoption of the Safe System framework and Vision Zero in research and practice, and lacks the emphasis on eliminating fatal and serious injury outcomes entirely. This paper, therefore, revisits the issue of tram stop safety by exploring whether current practices are aligned with Safe System framework principles, why or why not they might be consistent with the stated goal of Vision Zero, and how current and emerging practices might be adapted towards helping to virtually eliminate serious injury and death. A case research methodology is adopted, examining stops in Melbourne, as a first step towards future studies that might involve cross-case comparison with streetcar, tram and light rail systems elsewhere. Findings suggest a need to adjust practices related to stop design and management to bring them into alignment with the Safe System and Vision Zero. Directions for future research are also discussed.

1 Introduction

Where Light Rail Transit (LRT) operates as a streetcar or tram in mixed-traffic conditions it is often close to pedestrians, cyclists and other road users. However, LRTs: 1) are much heavier than most other vehicles, meaning they may take longer to stop; 2) cannot swerve to avoid collisions because they are on fixed tracks; and 3) typically operate in the centre of the road, meaning that passengers may have to cross traffic lanes before boarding or after alighting to get to or from the footpath. Hence, safety issues relating to LRTs and their stops may vary from those of other transit modes, in that buses are lighter (and so may stop more quickly) and have kerbside stops, while trains operate in fully-separated Rights Of Way (ROWs) with boarding and alighting at stations.

Vision Zero and the Safe System framework are based around the ideas that roads need to be forgiving of human error, and that the consequence of a failure in the system should never be death or serious injury (PIARC 2015). While there is much research about safety around LRTs, this field does not yet appear to have fully engaged with Vision Zero, the Safe System,

and the associated paradigm shift in road safety engineering and risk management. This paper, therefore, seeks to improve understanding of how Vision Zero and the Safe Systems framework are relevant to LRT safety. The aim is to update previous research into safety at tram stops in Melbourne (Currie & Reynolds 2010) to reflect the new understanding of safety provided by the Safe System framework and Vision Zero. More specifically, the paper tests the hypothesis that current practices related to tram stops are Safe System aligned.

The remainder of the paper is structured as follows: the next section discusses the context, including previous research about LRT safety, Vision Zero and the Safe System framework. This is followed in Section 3 by a discussion of the case research approach adopted for this study. Results are shown in Section 4 and discussed in Section 5, which concludes the paper.

2 Research context

Figure 1 shows a timeline of LRT-safety-related research, together with key developments related to Vision Zero and the Safe System framework.

Figure 1: Timeline of LRT stop safety research and developments in Vision Zero

Source: Authors[1].

Safety around streetcars, trams and LRTs has received much attention in the research literature and has also been the subject of multiple Transit Cooperative Research Program (TCRP) studies. Much of the focus of the first of these, Korve et al. (1995), is on collisions between LRTs and other vehicles, but there are also recommendations relating to passengers and pedestrians including increasing queuing space and safe zones at stops, fencing LRT ROWs, and installing sidewalks, gates and Z-crossings[2]. Although this work predates the widespread introduction of the Safe System framework, at least outside Scandinavia, it does note the problem of "pedestrians jaywalking across LRT/transit mall rights-of-way after receiving unclear messages about crossing legality" (Korve et al. 1995). In general, however, the research literature shown in Figure 1 does not appear to engage significantly with Vision Zero or the Safe System, even though much of it comes from after the shifts in policy in the 1990s in the Netherlands and Sweden, and in 2008 by Australia states, territories and national bodies. However, this is not unexpected, as widespread adoption and changes to practice take time – for example, it was not until the Morgan et al. (2018b) update that Australia's Road Safety Audit (RSA) guide fully incorporated concepts from Vision Zero and the Safe System framework. As well, LRT-specific research might also by expected to focus on emerging issues directly related to LRT technology, rather than new developments in road safety.

[1] Based on Eitan et al. (2023); Turner et al. (2016a); Lyon & Turner (2017); Turner & Lyon (2017); Morgan et al. (2018a); PIARC (2015); and SafeTREC (undated)).

[2] The term 'Z-crossings' refers to the arrangement of pedestrian fencing around track or roadway crossing points such that pedestrians face the direction from which vehicles are approaching as they themselves approach or cross the track or roadway. See Korve et al. (1995) and others for examples.

Vision Zero and the Safe System framework question the inevitability of road trauma and common attitudes that crashes are often (primarily) the result of road user error. Rather, these newer approaches emphasise that human error is inevitable, meaning that roads should be designed, managed and operated such that the consequences of such an error, a poor choice or other failures should **never** be major trauma or death. They also posit that responsibility for safety lies primarily with road designers and managers, rather than users, and that focus should be on eliminating hazards or reducing the consequences to eliminate fatality or serious injury (PIARC 2015; Lyndon & Turner 2017; Turner & Lyon 2017; Morgan et al. 2018a).

The Safe System framework has similarities to the fail-safe engineering principles used in railways, and which sometimes apply to LRT where it operates with block signalling systems and/or in a fully-separated ROW. Railway safe-working practices often involve a token or signal that gives a driver the authority to operate on a track section, including at speeds higher than at which the train could be stopped within the amount of track visible ahead. Safe operation is assured because each track section either has only one token or an interlinked signalling system such that only one train can operate on each track section at a time. However, when driving on the road as a streetcar or tram, LRTs are, like other vehicles, typically driven by line-of-sight and according to traffic rules, which include positive duties to give way at intersections or other points of potential conflict. Safe operation tends to rely on road users acting according to road conditions, and slow enough to avoid collisions.

Road crash data is often used to identify high-risk areas, explore casual factors, and develop or select countermeasures to resolve issues. Such data-driven approaches have been used in much of the previous research about LRT safety shown in Figure 1. However, road crashes are infrequent events that occur somewhat at random, and so past history is not necessarily a perfect predictor of current or future crash risk. Such data-centric approaches are also reactive, and so there are obvious moral problems with waiting for deaths and serious injuries to occur before intervening.

Various proactive approaches have been developed for improving road safety, including risk-based safety programs (e.g. iRAP, ANRAM, KiwiRAP). Road Safety Audits (RSAs) are a commonly used process that involves an independent team assessing an existing road, proposed design or traffic management scheme solely from a safety perspective (Turner et al. 2016; Turner et al. 2017; Morgan et al. 2018a, 2018b). Part of this process involves rating each identified risk, and Figure 2 shows the assessment matrix currently used in Australia.

Figure 2: Safe System risk assessment guidance. Source: Hillier (2022).

			Severity*				
			Insignificant	Minor	Moderate	Serious	Fatal
			Property damage	Minor first aid	Major first aid and/or presents to hospital (not admitted)	Admitted to hospital	Death within 30 days of the crash
Likelihood (includes exposure)	Almost Certain	One per quarter	Medium	High	High	Extreme (FSI)	Extreme (FSI)
	Likely	Quarter to 1-year	Medium	Medium	High	Extreme (FSI)	Extreme (FSI)
	Possible	1 to 3 Years	Low	Medium	High	High (FSI)	Extreme (FSI)
	Unlikely	3 to 7 Years	Negligible	Low	Medium	High (FSI)	Extreme (FSI)
	Rare	7 years+	Negligible	Negligible	Low	Medium (FSI)	High (FSI)

*see Severity Guidance Sheet

Safe System crash outcome threshold

This matrix includes a “Safe System crash outcome threshold”, separating crashes with Fatal and Serious Injury (FSI)[3] outcomes from less severe incidents. For risks assessed as being above this threshold there is a need to eliminate the hazard entirely or to introduce measures that reduce the consequences of any crash that does occur to be, at most, only moderate injury (e.g. through speed reductions or the installation of a crash barrier so that impact forces are within the limits of human tolerance).

Hillier (2022) provides guidance as to speeds and types of crash which might have FSI outcomes. Crashes involving heavy vehicles and pedestrians are shown as potentially having FSI outcomes at impact speeds greater than 10km/hr, while those involving pedestrians and cars might exceed the FSI threshold at impact speeds of 20-25km/hr or higher. Of relevance to this study are the findings of Gaca & Franek (2021), based on data from Warsaw and Krakow, of fatality risks for pedestrians in tram-involved crashes being 22, 38 and 58 percent at impact speeds of 20, 30 and 40km/hr respectively. This compares to estimates of just 2, 5 and 14% for pedestrians in car-involved crashes at the same speeds (based on a summary of 15 studies from 1980 through 2015). While it is unclear what the equivalent values might be for (just) serious injury outcomes, these results perhaps are indicative of the reality that humans are fragile and can potentially be seriously hurt or killed by large and heavy objects moving at almost any speed. This has long been understood in Occupational Health & Safety (OH&S) contexts, for example with respect to safety around forklifts (Larsson et al. 2003; Victoria 2010), but on road systems minimal separation of people from traffic is accepted[4].

The shift towards greater use of approaches informed by Vision Zero and the Safe System framework provides the motivation for this paper. Previous research leveraging an RSA-based methodology to assess Melbourne’s tram stops (Currie & Reynolds 2010) predates widespread adoption of Vision Zero and the Safe System framework, at least in Australasian practice, and so lacked the emphasis on eliminating the risk of FSI crashes entirely. This paper seeks to fill this gap, both with respect to adopting an RSA-based methodology to assess the Melbourne tram network, but also for research related to safety at and around streetcar, tram and LRT stops more broadly.

3 Methodology

This study adopts a similar approach to that used in Currie and Reynolds (2010) by examining the Melbourne tram network as its single case. Case research is well suited to exploratory and theory-generating studies, as is the situation here, and the methodological literature provides guidance on case study design including how many cases to include, and the theoretical and other reasons specific cases might be chosen (Yin 2009). Although there is an extensive body of methodology literature supporting the scientific rigor, replicability and generalisability of case research it is sometimes misunderstood or criticised by those more familiar with other approaches, especially those that use random and larger samples, and seek statistical significance (Eisenhardt & Graebner 2007). Case research instead seeks to be grounded in the context of a small number of cases, allowing great depth, yet at the same time to be seeking generalised findings that also apply to more than just the examined cases. This is known as the “duality criterion” (Ketokivi & Choi 2014), which Denscombe (2007) suggests researchers should respond to directly so as to provide “an explicit defence against the allegation that you cannot generalize from case study findings”. This is done in the following.

[3] This paper adopts the ‘FSI’ term throughout, for consistency with Austroads publications (i.e. Hillier 2022). Terms used can vary, including by jurisdiction (e.g. Death and Serious Injury (DSI) adopted in the New Zealand Road Safety Strategy 2020-2030).

[4] IKEA’s typical ‘warehouse’, check-out and loading bay arrangements provide a stark example of how different regulatory environments might set different standards. Inside the ‘warehouse’ the public and forklifts are never present at the same time, because these are not compatible under OH&S laws or practices related to public safety and liability. Outside, in contrast, one-to-two-tonne pieces of metal often operate in close proximity and sharing space with fragile people, because parking lots and loading bays operate according to road system rules.

This paper is expected to be the first in a larger program of research looking at safety around LRTs in a variety of contexts. Overall, this would involve adopting a multiple holistic design, in which streetcars/tram systems are the main units of analysis (the cases), with stop types as sub-units. This paper, however, reports only a single case, which is selected because Melbourne has the largest streetcar/tram network in the world (250kms of double-track of which approximately 75% is within mixed traffic)(Currie & Shalaby 2007). Melbourne therefore provides a leading case and the potential for more generalisable results, as if common practices across the (global) LRT industry already have an emphasis on (virtually) eliminating FSI outcomes then this might be reasonably expected to be evident on the world's largest mixed-traffic LRT network, especially for the newer types of stops (platforms and easy-access) and where stops have more recently been upgraded. Melbourne is also a convenient case for the commencement of this program of research, given the researchers' location, but it is also likely to be generally representative of the legacy streetcar/tram networks existing in many other cities (e.g. Toronto). Selecting Melbourne also opens opportunity for replication and examination of polar opposites in future cross-case comparison with Toronto.

Like Currie and Reynolds (2010), this study uses the current Austroads RSA guidance to inform the methodology, especially with respect to identifying and assessing hazards common to each of the stop types found in Melbourne[5]. The intervening years have seen the introduction of Safe System Assessments (SSAs) as in Turner et al (2016), which includes a system to rate exposure, likelihood and severity across run-off-road, head-on, intersection, other, pedestrian, cyclist and motorcyclist dimensions to produce a total assessment score. Some road authorities have brought RSAs and SSAs together into a single assessment approach (e.g. Waka Kotahi NZ Transport Agency (2022)), although Hillier (2022, p.19) notes that "…despite their apparent similarities, a contemporary RSA under the Safe System and a Safe System Assessment (SSA) are not identical but can be complementary". This study, therefore, adopts the same RSA-informed approach so as to be consistent with Currie and Reynolds (2010), rather using detailed scoring on a site-by-site basis or other elements of a SSA. As well, this paper focuses on identifying issues where the consequences might be above the FSI threshold, and (as the focus is on stop-types) does not seek to quantify likelihood because of this might vary considerably from stop to stop based on passenger and traffic volumes, and many other factors.

3.1 Case context

The Melbourne tram network has 25 routes, around 500 trams, 9 types of tram (including high- and low-floor vehicles) and over 1,700 stops, almost all of which are either: platform, easy access, safety zone or kerb-side stops. Platform and easy access stops are elevated, allowing step-free access to low-floor trams. Safety zone and kerb-side stops, however, are at road surface level, with passengers needing to step up to board both low- or high-floor trams. The network is currently in transition to be 100% low-floor and step-free to meet the requirements of the Disability Discrimination Act (1992), and it was this that led to the development of the platform and easy access stop types (Currie & Smith 2006; Currie & Shalaby 2007).

Stop types were assessed by one of the authors, who is accredited with the Victorian Department of Transport and Planning as a Senior Road Safety Auditor. For this research Google Streetview imagery was used to review various location as: 1) the researchers regularly use the Melbourne tram and road networks, and so already have familiarity with the examined stop types; 2) more stop-type variations could be assessed using remote imagery in the time available; 3) use of Google Streetview imagery promotes reproducibility of this research, as anyone can examine the stops shown as examples in this paper for themselves[6];

[5] In Currie and Reynolds (2010) this was the third edition of the Guide to Road Safety Part 6: Road Safety Audits, published in 2009, whereas here it is the sixth edition, (Hillier (2022)). Sub-units of the case study are, also as in Currie and Reynolds (2010), the four stop types found in Melbourne: platform, easy access, safety zone and kerb-side stops; while individual stops on the network are highlighted where appropriate and as indicative examples of issues common to each stop type.

[6] Hyperlinks are provided in the electronic versions of this document that link to the relevant locations.

and 4) site visits are themselves potentially hazardous (to the researchers) as far as being around vehicles, looking at sites from angles close to or within active traffic lanes, or otherwise, which appeared unnecessary as the study is about the stop types, rather than specific individual stops themselves.

Various tram stops across Melbourne were reviewed for this study, including on the approach (near-side) or departure from intersections (far-side), mid-block, at terminals and at interchanges across the four stop types: safety zones; kerb-side; platform and easy-access. Safety zone stops are located in the middle of the road, with a fenced area for passengers to wait, board and alight, as shown in Figure 3.

Figure 3: Safety zone stops (sign circled[7]). Sources: Google Streetview.

a. Near side, with (yellow) 'prow' b. Near side, no (yellow) 'prow'.

Kerb-side stops are typically denoted by the stop sign behind the kerb, as shown in Figure 4. Passengers step cross the traffic lane to/from the footpath and kerb while a tram is at a stop, with traffic rules requiring other road users to halt while boarding and alighting is taking place.

Figure 4: Kerb-side stops (sign circled). Sources: Google Streetview.

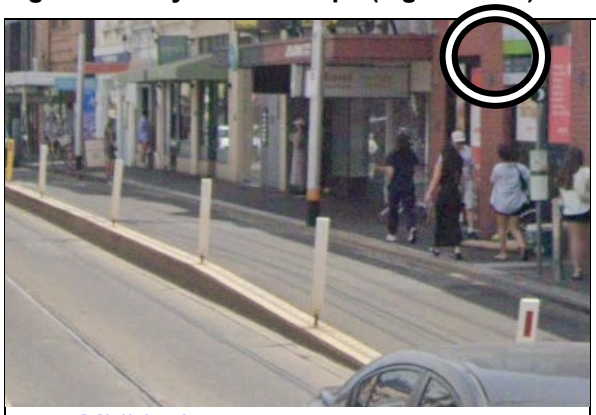
a. Near side b. Near side (central carriageway)

Easy access stops are a Melbourne innovation, developed to convert a kerb-side stop into one that has level-boarding access to a low-floor tram, as described in Currie and Smith (2006). As Melbourne's trams do not have extendable ramps (as in Toronto), to provide level-boarding access to low-floor trams it was necessary to raise one of the traffic lanes, as shown in Figure 5.

Figure 6 shows examples of platform stops, which are common at inner-city and higher-volume locations, but are also often found where space is available within medians.

[7] A sign showing route and other details, often mounted on a pole, is placed at the passenger waiting area at stops (closest to the point at which the front of the tram will stop).

Figure 5: Easy-access stops (sign circled). Sources: Google Streetview.



a. Midblock

b. Docklands / Harbour Esp northbound

Figure 6: Examples of Melbourne's platform stops (sign circled). Sources: Google Streetview.

a. Side platform, far-side

b. Island platform, ped signals

c. Side platforms opposite each other (far-side and near-side)

d. Zebra crossing and flashing light tram crossing (pedestrians give way to tram)

Some consist of a pedestrian-only island platform serving both directions, but requiring boarding from the right side of the tram (Figure 6b.). Others have platforms for each direction (a., c. & d.) with passengers boarding from the left, as is typical at most stops. Access is usually at the ends via signals, a zebra crossing or an uncontrolled crossing, typically with ramps, although some have stairs or only one accessible end.

4 Results: risk assessment and potential mitigations

4.1 Stops in general

4.1.1 Centre of the road – other traffic

Because trams operate in the centre of the roadway passengers need to cross traffic lanes twice during most journeys, when (or before) boarding and when (or after) alighting. Even where trams operate in a median, well clear of traffic lanes, passengers still usually need to cross roads at grade. Some stops are at traffic signals, pedestrian operated signals or zebra crossings, and such measures might decrease collision likelihood. However, these do not tend to eliminate the possibility of fatality or serious injury entirely[8]. However, at many signals

[8] There is extensive literature on how much specific treatments might be expected to reduced crash rates, and the Crash Modification Factors Clearinghouse provides statistical values for various measures. Some include consideration of how a measure might impact FSI crashes, but detailed examination of this (and how it might apply to different stop types) is considered beyond the scope of this paper (given it is an exploratory case study).

passengers only have to cross one or two lanes to reach the footpath, which may increase the likelihood of jaywalking, unexpected pedestrian movements and/or collisions, especially if cycles are long[9], although there may be interaction effects where shorter crossing distances reduce exposure.

Traffic calming (such as speed humps) would appear to be a potential option, matching the approach long-used at 'wombat' (raised zebra) crossings, and emerging directions related to raised intersections (see Blewden et al. (2020)) to reduce traffic speeds and crash severity.

4.1.2 Centre of the road – tram traffic

Passengers often need to also cross tram tracks to reach or depart stops, exposing them to the risk of collisions involving a tram. These might result in serious injury or fatality even at low impact speeds given that trams weigh in the order of 30-50 tonnes, cannot swerve, and take a considerable distance to stop even under emergency braking. Near-side stops are common across the network, which may increase risks associated with passengers trying to cross in front of a tram they just disembarked (as it departs), or lack of sight lines to trams travelling in the opposite direction if walking to the back of their tram and crossing the tracks behind.

Some crossing points are signal controlled, while others require pedestrians to give way to trams. In some cases, pedestrian operated traffic signals do not apply to trams, meaning that pedestrians might cross traffic lanes on a green 'walk' signal, but then immediately have to give way to a tram. Such treatments may have the potential to catch pedestrians unawares, as it is typical at most signalised intersections to continue to cross the entire roadway when a green 'walk' signal is displayed. Figure 6d. shows an example in the context of zebra crossings, where pedestrians are required to give way to trams, yet only a few metres away might reasonably expect that approaching traffic will give way to them[10]. All of these contrast to heavy rail crossings, which tend to be grade-separated or have automatic gates to eliminate the potential for a pedestrian to be struck by a train (assuming compliance by pedestrians).

Tram drivers are clearly trained to be vigilant around pedestrians. However, there remains, especially in busier environments, the potential for pedestrians to jaywalk or otherwise be in the path of a tram due to the lack of grade separation or physical barriers.

4.2 Platform stops

4.2.1 Platform edges

Platforms are in the order of 300mm above the road surface, with a relatively large drop-off immediately next to the passenger waiting area. At some stops there is fencing between the tracks or otherwise that might help to discourage passengers from crossing directly to/from the stop without using the ramps or stairs provided. However, slips, trips and falls related to the platform edge and collision with trams themselves appear to be potential hazards that might result in serious injury or otherwise. Most platform stops have some form of delineation (often including tactile markers) close to the platform edge, but this relies on passengers themselves to stay clear of the platform edge and arriving and departing trams, and may not be sufficient under all circumstances (e.g. crowding, wet and slippery etc.) or for all users (e.g. small children, those who have mobility or visual impairments, large groups, intoxicated etc.).

There may be some potential for softer surfaces between the tracks, such as through the use of grass rather than concrete (Novales & Conles 2012) or increased platform widths, and/or additional separation between the edge of platforms and tactile markers and other delineation.

[9] Where tram stops are located at intersections with more complicated traffic signal cycles (e.g. 4-phase diamond sequences, fully-actuated signals or where phases are dynamically adjusted to provide transit priority), the likelihood of jaywalking-related collisions appears higher, given that: pedestrians may incorrectly predict the current or next traffic phase and so step into the path of traffic facing a green arrow or similar; and cycle times tend to be longer, increasing the likelihood that a pedestrian might not wait for their green signal.

[10] At this particular location there are red "don't walk" symbols mounted in bollards that are triggered to flash by approaching trams, but this appears an extremely uncommon treatment.

However, better understanding how physical segregation of passengers from the platform edge and trams might be achieved[11] appears a direction for future research.

4.2.2 Ends exposed to passing traffic

With ramps and/or stairs at the ends of platforms, passengers who are waiting to cross to the footpath might often be exposed to oncoming traffic. OmniStop bollards[12] are present at many stops and these can provide a crash-worthy treatment at low speeds (Figure 7a.). However, such bollards are not present at all stops, and they do not necessarily cover all areas that pedestrians use.

Figure 7: Selected imagery from tram-stop-related crashes.

a. OmniStop bollard

b. Roll-over at tram stop

c. Off easy-access stop

d. Speared by stop fencing

e. Collision with fencing

f. Collision with fencing

Sources: Yahoo, Herald Sun, Reddit, Herald Sun, Daily Mail, Yahoo.

As well, the stops, bollards and other fencing may pose a risk to vehicle occupants, including the potential to flip errant vehicles or as a spearing hazard (Figure 7d.). In some instances, the bollards and fencing appear insufficient to prevent collisions with passengers, and might

[11] Some railways are shifting towards platform screen doors to prevent passengers falling onto or otherwise entering the tracks. Whether a similar approach is practical in mixed-traffic is unclear, but appears unlikely.

[12] This type of bollard (typically white, with red and yellow striping) has a replaceable base that gives a small amount in the case of a crash to reduce impact forces experienced by vehicle occupants.

also be something a pedestrian could be pinned to in a crash (e.g. Figure 7a.), especially if they are waiting on the 'outside', closest to the traffic lane[13].

4.3 Easy-access stops

4.3.1 Platform edge

In general, similar trip, fall or other potential hazards related to the drop-off between the platform and track level appear to exist at easy-access stops as at platform stops (as discussed in 4.2.1)[14], although at easy-access stops passengers may be less likely to be near the hump edge when the stop is not occupied by a tram.

As well, as the platform itself is traversable by traffic there appears to be potential for crashes involving a vehicle dropping off the edge itself or travelling up the approach ramp with one set of wheels in each traffic lane (see Figure 7c.), which might result in a rollover or other severe crash type. Installation of traffic islands, crash-worthy bollards or other protection to separate traffic on the 'upper' side of the easy-access stops from the drop-off may provide one way to further reduce risk, as already used at a Docklands stop (see Figure 5b.).

Easy-access stops and kerb-side stops

4.3.2 Centre of the road – other traffic

The need to cross traffic lanes to board/alight appears to be a similar problem at easy-access and kerb stops (as at other stop types, see Section 4.1.1). However, the likelihood of such a crash appears to be higher at easy-access and kerb-side stops given that passengers have to cross active traffic lanes as part of the process of boarding/alighting a tram. A road rule requires other road users to halt behind a stationary tram with its doors open, but this appears likely to be breached (when considering the network as a whole) through human error, driver unfamiliarity, intentional disregard or otherwise on a daily (or more frequent) basis. Near-side stops at traffic signals appear to be of particular concern due to the potential for driver error related to cognitive dissonance if there is a tram with its doors open (requiring a driver to stop) on the immediate approach to a green traffic signal (suggesting a driver should go). The need to stop at far-side and mid-block easy-access or kerb-side stops might also be unexpected by approaching drivers, who may have relaxed their attention on departing a prior intersection.

4.3.3 Exposure to traffic while waiting

Passengers waiting at easy-access and kerb-side stops typically do so immediately beside a traffic lane, typically on the footpath. For kerb-side stops the edge of the traffic lane is clearly defined and separated (by the kerb) although not physically segregated (e.g. by fencing, crash barrier etc.), meaning there is potential for passengers to inadvertently step into the path of oncoming traffic (e.g. a small child, an intoxicated passenger or otherwise), as well as introducing a hazard related to trips or falls because of the kerbing itself. At easy-access stops the edge of the traffic lane is not clearly defined by a level change, which might increase the likelihood of human error, even where delineation and/or tactile markers are present.

There may also be risks associated with errant vehicles impacting the passenger waiting area. Crash barrier at stops may have been avoided previously due to the risk of barriers

[13] This hazard is related to the discussion above about trams operating in the centre of roads. However, relocation of stop access to the middle of platform stops, or additional separation of areas in which passengers wait to cross the road from adjacent traffic lanes might reduce the likelihood of severe injury or fatal outcomes. Another alternative might be to stop traffic entirely while alighting passengers are crossing between the tram and the footpath (as is the case at kerb-side and easy-access stops), perhaps through coordination of existing traffic signals so that a red signal is shown to traffic between the time that alighting commences and when passengers have reached the relative safety of the footpath, thereby eliminating the need to wait at or close to the end of platforms.

[14] However, fencing between the tracks or otherwise to discourage direct crossing of the traffic lanes where the drop-off is located, as at some platform stops, are not known to exist at any of Melbourne's easy-access stops.

themselves[15]. A Vision-Zero-informed approach, however, might suggest a need for crash barriers to prevent errant vehicles entering the areas where passengers wait, even at low-used stops and even in low-speed environments. The stop in Docklands mentioned above (Figure 5b.) provides an example where OmniStop bollards separate the traffic lane from the stop waiting and shelter area.

4.4 Safety zone stops

4.4.1 Proximity of trams and traffic

Most safety zones are narrow, often with space enough for only two people to pass each other between the fencing and a tram. Linemarking is often provided to delineate the passenger waiting area, but there is no physical barrier to people stepping into the path of a tram.

As well, those waiting within a safety zone are often in close proximity to passing traffic in the adjacent traffic lane. Safety zone fencing does not appear to be sufficient to always prevent an errant vehicle from impacting a passenger, while it is also common to see those waiting leaning against the fencing itself. This might result in passengers (clothing, baggage or otherwise) becoming snagged on a passing vehicle, passengers leaning into the traffic lane enough that they are impacted by a passing vehicle, or for parts of a vehicle that overhang (e.g. side mirrors on a truck) entering the space occupied by a waiting passenger.

4.4.2 Vehicle roll-over

Many safety zones have a large yellow ‘prow’ on the approach side (Figure 3a.). This appears increase the risk of a roll-over if a vehicle impacts a stop.

5 Discussion

5.1 Eliminating centre-of-the-road operation near stops (long-term)

The imagery in Figure 7 perhaps demonstrates that collisions with tram stops can involve significant crash energies that might exceed the limit of human tolerance in the event that a passenger or other pedestrian is hit, or for vehicle occupants hitting platforms or fencing. Spearing hazards (Figure 7d.) and roll-overs (Figure 7b.) appear most likely to result in serious injury or death for vehicle occupants, but other crash types might also have the potential to exceed the Safe System threshold, particularly in higher-speed environments and at kerb-side or easy access stops where passengers cross lanes and only a law halts traffic.

Bus passengers typically board and alight directly from/to the footpath, and it is common for buses to run in the kerb-side lane between stops. When buses run in other lanes passengers are typically carried back to the kerb-side at stops while on board the bus itself. Such weaving movements might add risks related to bus-to-vehicle collisions, but these appear much less likely to result in serious injury or fatal outcomes than crashes involving passengers who are not inside a transit vehicle. Kerb-side running of streetcars/trams, even if only close to stops, however, appears to be uncommon. This may be mostly for historical reasons and because of path dependence. Further research might explore the potential for moving tram stops and the associated boarding/alighting activities to the kerb, in that: while this might introduce the potential for merge/diverge crashes if trams change lanes, such potential conflicts only exist when a tram is actually present; in contrast, centre-of-the-road tram stops are a potential crash hazard to other road users at all times. Likewise, the risks associated with crossing to/from the footpath are currently spread out in time, occurring as each individual passenger crosses the traffic lanes. Moving passengers across the traffic lanes together, in a group within trams, might therefore reduce exposure (in time) and provide the extra protection of being within a tram itself.

[15] With the logic being that a crash barrier increases risk for errant motorists at all times, whereas the risk to passengers from errant vehicles only existing when passengers are actually there.

Clearly, however, if shifts to current practices related to centre-of-the-road operation are to be adopted these might take some considerable time to implement, and may raise other safety issues or face challenges related to political, institutional or other non-technical factors. Previous research on priority implementation (Reynolds & Currie 2021) might suggest the use of bottom-up and incremental approaches (i.e. taking advantage opportunities on a site-by-site basis) or the adoption of a long-term, vision-based plan along the lines of seeking to "minimise the need for tram passengers to cross active traffic lanes while boarding and alighting as much as is technically possible". In the meantime, however, the findings of this study might suggest shorter-term changes to practices, including some already in use in Melbourne, as discussed in the following.

5.2 Kerb-side and easy-access stop: Intelligent Transport Systems

Kerb-side and easy-access stops appear to be of particular concern, given that these are entirely reliant on driver behaviour to maintain safety. In many places it is possible for the traffic law to require a vehicle to stop behind a tram while a traffic signal at a nearby intersection or crossing displays a green signal. Technological solutions that allow bus door sensors to be linked to transit priority systems so as to precisely time signal phases to bus stop departures have already been described in the research literature (see Hounsell et al. (2008)). Such approaches might be adaptable to tram stops so nearby traffic signals always display a red signal whenever tram doors are open, which suggests a direction for future research and development, including with respect to conformance with traffic laws, institutional and public acceptance, and compliance rates.

However, while such directions might reduce crash likelihood, they appear unlikely to completely eliminate FSI crash outcomes related to trams being in the middle of roads. Boom gates at stops or other physical barriers (including tram-mounted) might be an avenue for future research, perhaps leveraging technology associated with the Truck-Mounted Attenuators (TMAs) that are now commonly used for mobile roadworks (see Mosunmola Aroke et al. (2022)), and which might be deliverable in the medium term.

5.3 Tram-&-pedestrian-involved fatal/serious injury crash potential

In mixed-traffic environments passengers typically cross at track-level, and many do so in front or immediately behind the streetcar/tram that they have just alighted from or intend to board. Such movements raise the possibility of being hit by the tram just alighted from, one that someone is about to board, or one traveling in the opposite direction. Even at stops where there is clear separation of trams and passengers, such as at platform stops, complete segregation such as might be found in a modern subway or other heavy rail environment (including platform screen doors) does not appear to currently be feasible. This suggests a need for further research to better understand how passengers and trams might be physically segregated in mixed-traffic environments, but with boarding and alighting still possible, including whether platform screen door technologies might be adapted to LRT.

Some current practices in Melbourne appear to already be reducing or coming close to eliminating some risks related to the interaction of trams and pedestrians. Fencing between the tracks appears to help by physically blocking pedestrian desire lines, but Figure 7d. shows that this itself may be a significant hazard to other road users (e.g. spearing hazards). This might suggest a need for further research to better understand which fencing types and layouts might be more effective at segregating pedestrians and trams, without the potential for fatal or serious injury for others.

Many railway crossings have automatically-controlled pedestrian gates. However, there appears to be a range of problems with this approach, including: activation of the gates having poor synchronisation with arrival of a train; and that it remains physically possible to evade the gates and cross anyway (see for example Larue et al. (2018)). Figure 6d. shows an implementation of tram-activated flashing "don't walk" signals at a platform stop in the

Docklands, although how well this works in practice with respect to the timing of the signals and whether this improves compliance is unclear, and research into this does not appear to have been reported in the literature. As well, this implementation remains reliant on pedestrians seeing and correctly responding to the signals, and there remains the potential for cognitive dissonance or other errors related to the close proximity of zebra crossings at which other road users are supposed to give way to pedestrians. A similar issue appears to exist at many pedestrian operated signals and other locations where pedestrians are required to give way to trams, but not other traffic. This might suggest opportunities for further research, including field studies to better understand the rate at which pedestrians might fail to check for or give way to trams. That said, the technology deployed in Docklands might provide an initial step towards automatic gates or similar that physically segregate pedestrians and trams (in time), and further assessing its impacts may be a direction for future research.

5.4 Crash-worthiness of stop infrastructure

Figure 7 shows the potential for serious injury or fatal crash outcomes where another road vehicle impacts a stop. Practices in Melbourne, however, appear to have improved recently with the removal of many safety zone ‘prows’, and with crash-barriers now present at many stops. The stop in Docklands shown in Figure 5b. may provide a model for future stop development, given the way that OmniStop bollards have been placed to prevent entry of errant vehicles into areas where passengers often wait. However, there may also be need for pedestrian fencing or other treatments to limit access and eliminate the possibility of a passenger being crushed between an errant vehicle and a bollard, crash barrier or otherwise. How practical this might be in mixed-traffic environments is unclear, and might be a direction for future research.

6 Conclusions

Findings from this case study of Melbourne suggest rejection of the hypothesis that current practices related to tram stops are <u>always</u> aligned with Vision Zero and the Safe System framework’s emphasis on eliminating serious injury and fatal crash outcomes. Given that Melbourne has the largest streetcar network in the world, and that Australian research and practice has tended to be at the forefront of the development and implementation of the Safe System, it would appear reasonable to expect that these findings would apply more generally to other streetcar, tram and LRT systems.

The various issues identified in this study and potential options are shown in Table 1.

Table 1: Summary of issues and potential options applicable to each stop type

	Stop type				Potential options longer term → → → → → → → shorter term					
Issue	**Platform**	**Easy-access**	**Kerbside**	**Safey Zone**	**Kerb-side tram operation near stops** (5.1)	**Tram-mounted technology** (4.3.2, 5.2)	**Softer surfaces** (4.2.1, 4.3.1)	**Pedestrian separation (gates, fencing, etc.)**(4.1.2, 5.3)	**Traffic calming** (4.1.1)	**Crash bollards, barriers etc.** (4.2.2, 5.4)
Pedestrians crossing traffic	✓			✓	✓			✓	✓	
		✓	✓		✓	✓			✓	
Pedestrians crossing tracks	✓	✓	✓	✓				✓		
Drop-off (falls) (4.2.1, 4.3.1)	✓	✓					✓	✓		
Exposure while waiting (4.2.2, 4.3.3, 4.4.1)	✓	✓	✓	✓				✓	✓	✓
Roll-over (4.3.1, 4.4.2)		✓		✓						✓

Note: References to relevant previous sections shown in small type numbers

In general, it appears that greater use of traffic calming, pedestrian separation measures and crash-worthy bollards/barriers may provide opportunities to respond to multiple issues

common across most or all stop types in the short term. As well, such measures mostly appear to be well proven, with commercial products already available. However, some research and development may be necessary with respect to separating pedestrians and trams yet still allowing for boarding and alighting (see discussion above in Section 5.3).

How softer surfaces might be used to reduce the risk of serious injury from falls off platform edges appears to be an open question, although grass track is already an established technology. However, this may not be worthy of further study given that any measures that eliminate the possibility of passengers and trams colliding at or near stops (e.g. adapting platform screen doors to LRT environments, developing fences/gates that still permit boarding/alighting, etc.) might also eliminate the potential for passengers to fall off platform edges. Similarly, the development of ITS technology, boom gates at stops, tram-mounted barriers or similar to address the problems of passengers crossing traffic lanes to board or during alighting at easy-access or kerb-side stops (see Section 5.2) would appear to be of limited value as a future research direction at the current time. Instead, the issue of safety for passengers boarding and alighting at kerb-side and easy access stops might be readily addressed with existing traffic calming technology (e.g. speed humps on stop approaches), while longer-term research efforts might be better directed towards exploring the possibilities and implications of shifting trams to kerb-side lanes at and around stops (if not also elsewhere).

More broadly, there appear to be opportunities for future research about the implications for LRT and other types of transit of the Safe System and Vision Zero's emphasis on eliminating fatal and serious injury crash outcomes. Section 3 touched briefly on opportunities to apply this RSA-informed approach to other LRT networks, allowing for cross-case comparisons. Applying a similar approach to the parts of LRT systems that are between stops, especially intersections, other potential conflict points and/or with an emphasis on specific road user types (e.g. LRT and track interactions with pedestrians, cyclists or motorcyclists), might also be a direction for further research. As well, here the RSA approach has informed the methodology, but (as discussed by Hillier (2022, p.19)) SSAs provide a different, but complementary, way of assessing alignment with the Safe System principles. Further research might seek to use an SSA-informed approach and, for example, adapt the Turner et al (2016) rating of exposure, likelihood and severity across the run-off-road, head-on, intersection, other, pedestrian, cyclist and motorcyclist dimensions to produce a total assessment score for different parts of LRT systems, and to compare between different systems themselves. There might also be opportunities to apply quantitative measures of FSI crash risk changes from specific measures (e.g. Crash Modification Factors (CMFs)) to conditions common at different stop-types (e.g. safety zones and platforms might be more commonly at signalised intersections), or revisit crash-data approaches (e.g. as used in Naznin et al. 2016) with a greater focus on FSI crash types, as per the Safe System approach.

There appears to be much opportunity to further improve understandings of the implications of Vision Zero and the Safe System for LRT safety, and transit operated in and around road environments more generally. Some of the newer stops in the Docklands (Figure 5b. and Figure 6d.) suggest that Safe-System-aligned approaches have already been introduced, at least in trial locations, on the Melbourne network. This might indicate that 'best practices' in stop design, and LRT systems more generally (including beyond the case studied here), are starting to or are already shifting in the direction indicated by Vision Zero. However, the effectiveness of newer technologies (e.g. the flashing bollard mounted signals for pedestrians) remain unclear, as do the extent to which pedestrians successfully watch for and give way to trams (when required) close to zebra crossing, pedestrian operated signals or other places where other traffic gives way to them is unclear. These issues, and the potential future research directions related to kerb-side-running, segregation, fencing and other areas identified in Section 5 might suggest ways that practitioners and academics can continue to contribute towards (virtually) eliminating fatal and serious injury crash outcomes on and around streetcar, tram and LRT networks.

References

Blewden, M, Mackie, H & Thorne, R 2020, *Effectiveness and implementation of raised safety platforms*, Austroads.

Cheung, C, Shalaby, AS, Persaud, BN & Hadayeghi, A 2008, 'Models for safety analysis of road surface transit', *Transportation Research Record*, vol. 2063, no. 1, pp. 168-75.

Cleghorn, D, Clavelle, A, Boone, J, Masliah, M & Levinson, HS 2009, *TCRP Report 137; improving pedestrian and motorist safety along light rail alignments*, Transportation Research Board.

Currie, G & Reynolds, J 2010, 'Vehicle and Pedestrian Safety at Light Rail Stops in Mixed Traffic', *Transportation Research Record*, vol. 2146, pp. 26-34, DOI doi:10.3141/2146-04.

Currie, G & Shalaby, A 2007, 'Success and challenges in modernizing streetcar systems: experiences in Melbourne, Australia, and Toronto, Canada', *Transportation Research Record,* vol. 2006, pp. 31-9.

Currie, G & Smith, P 2006, 'Innovative design for safe and accessible light rail or tram stops suitable for streetcar-style conditions', *Transportation Research Record*, vol. 1955, pp. 37-46, via Scopus.

Currie, G, Tivendale, K & Scott, R 2011, 'Analysis and mitigation of safety issues at curbside tram stops', *Transportation Research Record*, vol. 4, no. 2219, pp. 20-9, DOI 10.3141/2219-03.

Denscombe, M 2007, *The good research guide*, 2nd edn, McGraw-Hill International UK Ltd, Maidenhead, Berkshire, UK.

Eisenhardt, KM & Graebner, MA 2007, 'Theory building from cases: Opportunities and challenges', *Academy of management journal*, vol. 50, no. 1, pp. 25-37.

Eitan, AT, Smolyansky, E, Harpaz, IK & Perets, S 2023, *Vehicle and pedestrian safety at light rail stops in mixed traffic, Connected Papers graph*, viewed January 28 2023.

Farrán, JI 2006, 'Pedestrian and motor vehicle traffic control practices for Light Rail Transit: innovations in new Light Rail Transit system, Barcelona, Spain', *Transportation Research Record* vol. 1955, pp. 56-61.

Gaca, S & Franek, L 2021,'Pedestrian fatality risk as a function of tram impact speed', *Open Engineering,* vol. 11, iss. 1, pp. 1105-13.

Hillier, P 2022, *Guide to road safety: Part 6: Road Safety Audit*, edition 6.0, AustRoads, Australia.

Hounsell, NB, Shrestha, BP, Palmer, S, Bowen, T & D'Souza, C 2008, 'Differential priority for London's buses at traffic signals using iBUS', *15th World Congress on Intelligent Transport Systems and ITS America Annual Meeting 2008*, vol. 4, pp. 2267-76.

Ketokivi, M & Choi, T 2014, 'Renaissance of case research as a scientific method', *Journal of Operations Management*.

Korve, HW, Farrán, JI, Mansel, D, Levinson, H, Chira-chavala, T & Ragland, D 1995, 'Integration of light rail transit into city streets'.

Korve, HW, Ogden, BD, Siques, JT, Mansel, DM, Richards, HA, Gilbert, S, Boni, E, Butchko, M, Stutts, JC & Hughes, RG 2001, 'TCRP report 69; light rail service: pedestrian and vehicular safety', *TCRP Report*.

Kruszyna, M & Rychlewski, J 2013, 'Influence of approaching tram on behaviour of pedestrians in signalised crosswalks in Poland', *Accident Analysis & Prevention*, vol. 55, pp. 185-91.

Larsson, TJ, Horberry, T, Brennan, T, Lambert, J & Johnston, I 2003, *A guidebook of industrial traffic management & forklift safety*, WorkSafe Victoria, VIC, Australia.

Larue, GS, Naweed, A & Rodwell, D 2018, 'The road user, the pedestrian, and me: Investigating the interactions, errors and escalating risks of users of fully protected level crossings', *Safety Science*, vol. 110, pp. 80-8, DOI 10.1016/j.ssci.2018.02.007.

Lyndon, M & Turner, B 2017, 'Building a safe system for transport', in A Delbosc & W Young (eds), *Traffic engineering and management*, Seventh edition edn, Monash University Institute of Transport Studies, Clayton, Victoria, pp. 555-72.

Lyon, M & Turner, B 2017, 'Building a Safe System for transport', in A Delbosc & W Young (eds), *Traffic engineering and management*, Seventh edition edn, Monash University Institute of Transport Studies, Clayton, Victoria, pp. 555-72.

Morgan, R, Tziotis, M, Turner, B & Epstein, J 2018a, *Guide to road safety part 6: Road Safety Audit*, 1.1 edn, AustRoads.

—— 2018b, *Guide to road safety Part 6A: implementing Road Safety Audits*, 1.2 edn, AustRoads, Sydney, NSW, Australia.

Mosunmola Aroke, O, Sylvester Onuchukwu, I, Esmaeili, B & Flintsch, AM 2022, 'Countermeasures to Reduce Truck-Mounted Attenuator (TMA) Crashes: A State-of-the-Art Review', *Future Transportation*, vol. 2, no. 2, pp. 425-52,

National Academies of Sciences, E, and Medicine, 2007, *Audible Signals for Pedestrian Safety in LRT Environments*, Transportation Research Board, Washington DC, USA.

Naweed, A & Rose, J 2015, '"It's a Frightful Scenario": A Study of Tram Collisions on a Mixed-traffic Environment in an Australian Metropolitan Setting', *Procedia Manufacturing*, vol. 3, pp. 2706-13, DOI 10.1016/J.PROMFG.2015.07.666.

Naznin, F, Currie, G, Logan, D & Sarvi, M 2016, 'Safety impacts of platform tram stops on pedestrians in mixed traffic operation: A comparison group before-after crash study', *Accident*, vol. 86, p. 1, DOI 10.1016/j.aap.2015.10.007.

Novales, M & Conles, E 2012, 'Turf track for light rail systems', *Transportation Research Record*, vol. 2275, no. 1, pp. 1-11.

Novales, M, Teixeira, M & Fontaine, L 2014, 'Light Rail Transit urban insertion and safety: European Experience', *Transportation Research Record*, no. 2419, pp. 63-81.

Omatsu, T, Ohmori, N, Matsumoto, S, Okamura, K, Kumagai, Y & Harata, N 2011, 'Evaluation of a Safety System Using ITS Technologies for Streetcar Stops Without Safety Barriers', *International Journal of ITS Research*, vol. 9, pp. 93-100.

PIARC 2015, *Road safety manual: a manual for practitioners and decision makers on implementing safe system infrastructure*, World Road Association (PIARC), Paris, France.

Reynolds, J & Currie, G 2021, 'New approaches and insights to managing on-road public transport priority', in G Currie (ed.), *Handbook of Public Transport Research*, Edward Elgar Publishing Limited, Cheltenham, UK, pp. 172-201.

Richmond, SA, Rothman, L, Buliung, R, Schwartz, N, Larsen, K & Howard, A 2014, 'Exploring the impact of a dedicated streetcar right-of-way on pedestrian motor vehicle collisions: a quasi experimental design', *Accident*, vol. 71, p. 222.

Safe Transportation Research and Education Centre (SafeTREC) undated, *California Active Transportation Safety Information Pages (CATSIP); Safe System Approach to road safety*, UC Berkeley, viewed July 25 2023, <https://catsip.berkeley.edu/resources/safe-system-approach-road-safety>.

Tubis, A, Rydlewski, M & Budzynski, M 2019, 'Safety assessment of tram stops', *Journal of KONBiN*, vol. 49, pp. 431-58.

Turner, B, Jurewicz, C, Pratt, K, Corben, B & Woolley, J 2016, *Safe system assessment framework*, Austroads, Sydney, NSW, Australia, <https://austroads.com.au/publications/road-safety/ap-r509-16>.

Turner, B & Lyon, M 2017, 'Safe System solutions', in A Delbosc & W Young (eds), *Traffic engineering and management*, Seventh edition edn, Monash University Institute of Transport Studies, Clayton, Victoria, pp. 597-615.

Turner, B, Lyon, M, Reynolds, J & Sobhani, A 2017, 'Understanding road safety problems', in A Delbosc & W Young (eds), *Traffic engineering and management*, Seventh edition, Monash University Institute of Transport Studies, Clayton, Victoria, pp. 573-96.

Victoria, W 2010, *Forklifts and people don't mix; WorkSafe's expectations for separation of pedestrians and forklifts*, Victoria State Government, VIC, Australia.

Waka Kotahi NZ Transport Agency 2022, *Safe System audit guidelines; Safe System auditing procedures for transport projects; Road to Zero edition*, Wellington, New Zealand.

Yin, RK 2009, *Case study research: design and methods*, 4th edn, SAGE Publications, Thousand Oaks, CA, USA.