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Enhancing Tram Safety in Mixed-Traffic Systems: A Case Study of Melbourne's Tram Collision Factors and Improvement Strategies

Nan Shao[1,a,*]

[1]*The University of Melbourne, Melbourne, Australia*
a. nsshao@student.unimelb.edu.au
**corresponding author*

Abstract: Trams, a vital component of public transportation, operate within diverse environments ranging from fully segregated tracks to mixed-traffic systems. This study investigated tram collisions in Melbourne—a city renowned for its extensive and historic tram network—and explored both systemic and behavioral factors contributing to these incidents. The analysis identified key factors such as the arrangement of tram platforms, intersection design, right-of-way (ROW) regulations, tram driver behavior, and the actions of other road users. The study revealed that inadequate tram platform arrangements and suboptimal intersection designs are major contributors to tram collisions. Recommendations for improvement include implementing elevated, standalone tram platforms with protective barriers and accessible ramps, expanding the use of Hook Turn intersections, and integrating intelligent transportation systems to enhance traffic management. Additionally, addressing behavioral factors is crucial. Enhanced training for tram drivers and educational campaigns for pedestrians and other road users are proposed to improve situational awareness and adherence to safety norms. By addressing both objective systemic issues and subjective behavioral factors, this study aimed to enhance the safety of tram operations in mixed-traffic environments, ultimately reducing collision risks and improving public confidence in tram systems.

Keywords: Mixed-traffic, Tram collision, Safety issues, Melbourne tram system.

1. Introduction

Trams are a form of light rail public transportation that operates on fixed tracks located in the centre of city streets [1]. They operate in three types of environments: fully separated tracks from roads, tracks that are separated from other traffic but still cross shared intersections, and completely shared road systems where trams run alongside other vehicles in mixed traffic [2]. Based on these operating environments, tram systems are often referred to as mixed-traffic systems [1]. While many countries have light rail transit systems, those operating in mixed-traffic environments are particularly prone to safety issues.

These collision incidents pose significant dangers, not only potentially injuring vulnerable and unprotected pedestrians or passengers but also reducing public confidence in the reliability of the transit system. Given that tram networks are heavily dependent on their fixed routes with limited

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detour options, such incidents can cause major disruptions and delays [3]. Therefore, safety is a primary concern in the design, operation, and development of light rail systems, particularly tram systems. A substantial body of existing literature has begun to focus on the safety of trams within mixed-traffic systems, exploring various aspects and causes of this issue.

Currently, many countries around the world operate light rail transit systems. Although light rail vehicles operating in mixed traffic environments do not constitute the majority, it is precisely these tram systems operating in mixed environments that are most prone to safety issues. For example, in Currie & Smith's study in 2006, the United States was cited as an example: While only 15% of all tram track lengths in the United States are in mixed traffic conditions, over 90% of light rail transit accidents occur along these mixed traffic routes [4].

The safety concerns of tram in mixed traffic environments are particularly worrisome in Australia, which boasts over 270 kilometers of tram tracks, making it the largest and oldest light rail network in the world. Meanwhile, with cities and areas such as Melbourne, Adelaide, Perth, Sydney, and the Gold Coast planning, constructing, and/or operating new light rail projects, the construction of light rail in Australia is gradually revitalizing, and its scale is further expanding. Among these, Melbourne has the largest tram system in the world, with 29 routes and 250 kilometers of track length. However, of these, 167 kilometers of tram routes (approximately two-thirds, specifically 67% of the light rail system) operate in mixed traffic environments, a proportion that is significant on a global scale. Moreover, Australia's tram scale continues to evolve, necessitating a focus on safety in this area given the increase in operations, introduction of new trams, and technological advancements.

In this paper, the tram operation model in Melbourne will be regarded as a case study to explore the causes of tram collisions in mixed traffic environments worldwide. Firstly, typical tram collision incidents in Melbourne will be discussed. Secondly, key factors contributing to tram collisions, including the arrangement of tram platforms, the design of intersections and right-of-way regulations, tram driver behavior, and the actions of passengers, pedestrians, and other road users, will be analyzed in detail. Finally, the paper will provide recommendations for improvements based on the analysis of the discussed cases and collision causes.

2. Typical Tram Collision Incidents in Melbourne

On September 20, 2023, a severe tram accident occurred at the intersection of Victoria St and Nicholson St in East Melbourne. Unexpectedly, the accident involved not just regular vehicles but two trams colliding head-on at the intersection. Both tram fronts were heavily damaged, with shattered glass and debris scattered across the scene. According to eyewitnesses, one tram derailed and veered off track after the collision. Despite the severity of the crash, there were no reports of serious injuries, and the conditions of those involved were relatively stable. Emergency responders closed both directions of Nicholson St, significantly disrupting tram lines 35, 86, 96, and 30. Passengers were instructed to disembark at the tram stop behind the incident site and walk to the next two tram stops to continue their journey. Michelle Stevens, a tram passenger passing through the area, commented, "It's a bit inconvenient, but I hope everyone is okay." [5]

Similarly, on April 8, 3AW radio reported a tram accident near Elizabeth St by Queen Victoria Market in Melbourne, where a pedestrian was hit by a tram on Monday afternoon. The Victorian Department of Transport later stated that the man who was struck was conscious and had been taken to the hospital in critical condition. This incident was expected to impact several tram lines. A witness named Georgie described the scene to 3AW radio host Heidi Murphy, saying, "There was a loud 'bang' while I was on the tram, followed by an abrupt stop, and the doors opened. We thought it had hit a pole or something hard. After getting off, we saw a person trapped under the tram. Fire trucks, ambulances, and police cars arrived immediately. I hope they survive." Such tram-related accidents are frequent in Melbourne, partly due to the mixed-traffic system in which Melbourne trams operate.

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Melbourne's mixed traffic includes pedestrians, trams, passengers, private cars, bicycles, and motorcycles, with trams often running in the middle of the road. Passengers need to cross the street to reach the central tram stops, contributing to the relatively high number of tram collisions in Melbourne. However, there is limited precise data or news reporting on these accidents. This is because such incidents are sometimes excluded from accident records if they don't directly involve tram collisions. Additionally, pedestrian-related accidents lack formal event coding, and many entries lack specific details like location, injury severity, or vehicle direction. Reports are often made only when tram delays occur, or the tram driver considers the accident severe. Consequently, the lack of reporting and data on these collisions is a common limitation in studying tram collision issues in Melbourne.

3. Factors of Tram Collision Problems in Mixed Traffic Systems

Despite the multiple possible scenarios for tram accidents in mixed-traffic, including collisions between trams and vehicles, trams and pedestrians, passenger falls within trams, and tram-to-tram collisions, this paper will consider all types of collision factors. In addition, recognizing the different terminologies used for trams across various regions—such as tram, light rail, and metro—this paper will uniformly refer to these public transportation systems as "tram" and will examine all situations where trams share roads partially or fully with other traffic.

3.1. Arrangement of Tram Platforms

Due to the operation of tram tracks in the center of undivided roads under mixed-traffic conditions, pedestrians need to cross the roadway with mixed traffic to reach the platform when there is no dedicated platform at the stops. Consequently, these stops have been identified as a major source of pedestrian safety issues [6]. Existing research indicated that 82% of safety incidents related to trams involve conflicts between automobiles and pedestrians [7]. Thus, the relationship between platform setup and pedestrian safety had been primarily established through comparative analysis of stops with and without platforms in existing studies.

Naznin et al. using the before-after crash analysis method and a control group (CG) approach, found that after the installation of platforms at 15 selected stops in Melbourne, which previously lacked platforms, pedestrian-involved injury crashes decreased by 43%, and FSI (pedestrian-involved fatal and serious injury) crashes decreased by 84%, disregarding the increase in passenger volume. This result clearly demonstrated that compared to traditional stops without platforms, platform installations lead to narrower lanes [8], thereby reducing traffic speed and subsequently the frequency and severity of tram-pedestrian collisions.

Similarly, Currie and Reynolds, and Currie and Smith both used before-and-after comparative analysis to argue that improved platform setups significantly impact the reduction of tram-pedestrian collisions. Studies showed that at one of Melbourne's most important stops, St. Kilda Road-Federation Square, the old platform experienced an average of 5 accidents per year, which reduced to 2.3 per year (a 53% decrease) after the introduction of new platforms [7]. Currie and Smith found that existing tram stops lacked the traffic-calming effects provided by new platform designs, potentially leading to more collisions around platform areas [4].

Hence, through a comparative analysis, it can be concluded that one of the reasons for the unsafe operation of Melbourne trams in mixed traffic conditions is the inadequate arrangement of tram platforms. Due to the insufficient separation of pedestrians or tram passengers from vehicles at certain platforms, passengers are prone to accidents when crossing the road to reach the centrally located tram platforms.

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3.2. Design of Intersections and ROW Regulations

The design of intersections and the regulations regarding right-of-way (ROW) are additional critical systemic factors affecting the safety of mixed-traffic. Numerous previous studies had evaluated the impact of tram priority measures on road safety; however, the conclusions are inconsistent.

Naznin et al. reported a significant reduction in collisions following the implementation of tram signal and lane control measures in Melbourne [8]. Using the empirical Bayesian (EB) method for a before-and-after collision study, Naznin et al. analyzed collision data from 29 tram signal priority intersections and 23 tram lane priority arterial roads in Melbourne. They concluded that the implementation of tram priority measures resulted in a 16.4% reduction in collisions, further corroborating that the design of intersections and the regulations regarding ROW contribute to collision incidents under mixed- traffic conditions. Following this research, Naznin et al. conducted a focus group study from the perspective of tram drivers to analyze the design of intersections and ROW regulations. The 30 tram drivers surveyed indicated that lanes with tram signal priority were perceived as the safer system setup in Melbourne's tram network, and "Hook Turns" were identified as a safer form of signal priority handling [9].

Melbourne has employed the design of Hook Turn intersections in mixed-traffic since the mid-1950s, and it has been recently reintroduced to improve tram priority at CBD intersections. Using visualized crash conflict point diagram analysis and a series of safety data analyses, Currie and Reynolds demonstrated that intersections with Hook Turns had lower collision rates and better safety performance compared to traditional intersections without Hook Turns [10]. This intersection design has also been used in other regions, such as China and Canada, a highly relevant recent study by Richmond et al. used a quasi-experimental design to investigate the impact of ROW priority on pedestrian collisions in Toronto. The results showed a 48% reduction in pedestrian crashes following the implementation of ROW [11].

Therefore, in the absence of well-planned mixed-traffic roads, chaotic right-of-way (ROW) conditions can lead to a higher likelihood of collisions at intersections. However, Melbourne's implementation of signal control for the tram system is a highly effective measure in reducing tram collisions under mixed traffic conditions. Notably, the Hook Turn intersections, implemented in Melbourne since the 1950s, serve as a highly effective and safer form of signal prioritization in mixed-traffic scenarios.

3.3. Tram Driver Behavior

As the most direct participants in mixed traffic, tram drivers significantly impact the safety of the tram system. The safety of tram operations is influenced by various factors related to the drivers, including their experience, situational awareness, punctuality pressure, and organizational behavior. These elements collectively affect the driving safety of tram drivers.

Naweed and Rose, and Nazin et al. were among the first researchers to analyze tram driver behavior and their daily challenges as significant factors impacting tram safety in mixed traffic. Naweed and Rose collected data from Australian tram organization in three phases: the first phase involved reviewing existing tram collision incident reports, the second phase included on-site observations at high-risk locations identified in the reports, and the final phase involved semi-structured focus group discussions with 23 participants, including 13 tram drivers. The interviews and observations concluded that deficiencies in tram drivers' situational awareness, such as failing to anticipate passenger behavior, played a major role in many collisions and nearmiss incidents. Additionally, the pressure to maintain on-time operations posed significant stress for tram drivers [2].

Nazin et al. employed a similar methodology, conducting five focus group discussions with 30 tram drivers. They found that one possible cause of mixed-traffic collisions was tram drivers' inability

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to accurately predict the behavior and movements of other road users, making it difficult to adjust speed and avoid danger. Despite having emergency brake systems, this method could cause standing passengers to fall, leading Nazin et al. to find that tram drivers would avoid using emergency brakes whenever possible [9]. Both studies noted the challenges posed by the pressure to maintain on-time operations, with this pressure potentially negatively impacting driver performance and safety.

3.4. Actions of Passengers, Pedestrians and Other Road Users

Actions of other road users besides tram drivers, including passengers, pedestrians, and cyclists, are also considered potential factors in collisions within mixed-traffic conditions. Existing research indicates that distractions among passengers and pedestrians, disregard for traffic rules, and incidents of bicycle tires getting stuck in tram tracks can all contribute to tram collisions.

Castanier et al. conducted a survey to determine the perceived risk of collisions with trams among pedestrians, cyclists, and drivers. Analyzing feedback from 973 road users, they found that most respondents believed their likelihood of being involved in a tram collision was lower than that of others, which is comparative optimism. This suggested that most pedestrians and other road users underestimate the risk of collisions with trams in mixed-traffic conditions [12]. Subsequently, Marti et al., and Soczówka & Żochowska conducted more targeted analyses of tram and pedestrian interactions respectively. Marti et al. using methods such as Bern Accident Cluster Analysis, weighted comparisons, and accident photo analysis, found that pedestrians' attention might be distracted by smartphones or headphones, and physical obstacles could block their visibility, leading to tram collisions [13]. Soczówka and Żochowska analysed routes taken by passengers to different types of platforms, finding that one likely cause of tram-passenger collisions was passengers' non-compliance with traffic regulations while crossing roads to reach tram platforms [3].

Cyclists, as other road users, also pose collision risks with trams. Teschke et al. compared 87 bicycle crashes directly involving tram or train tracks, finding that 32% of injured cyclists had been in accidents directly involving tracks, with the majority caused by bicycle tires getting caught in gaps beside the rails [14].

Passengers, pedestrians, and cyclists, as other road users, are recognized as factors contributing to tram collisions in mixed traffic. As mixed traffic system covers a wide range of traffic participants and complex situations, collisions are more likely to occur. Most pedestrians and other road users tend to be overly optimistic about the possibility of collisions, leading to a lack of risk awareness while participating in traffic. Non-compliance with pedestrian behavior norms at crosswalks and typical distractions, such as looking at phones, further increase the likelihood of collisions in mixed traffic conditions.

4. Recommendations for Improvements

Based on the study of Melbourne's mixed-traffic system, the following recommendations for improvements are proposed to address the causes of various collision incidents.

To enhance safety and accessibility, more secure and accessible tram platforms should be implemented. Compared to traditional Melbourne tram stops, new tram platforms should be elevated, creating a standalone platform in the center of the road. Protective barriers should be installed on both sides to ensure passenger safety while waiting for trams. Additionally, these elevated platforms should feature ramps with appropriate gradients to allow wheelchair access. To ensure passenger safety when crossing the road to reach or leave the tram platform, it is crucial to enhance the pedestrian crossings and traffic signals on both sides of the platform. Installing warning signs to alert private car drivers and other road users to the presence of tram platforms and potential safety hazards

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is also recommended. Furthermore, tram platforms should be positioned away from high-traffic, congested intersections and instead placed in areas with slower, calmer traffic.

The Hook Turn intersections, implemented in Melbourne since the 1950s, have proven effective in reducing intersection collisions and should be more widely introduced and implemented in the central business district (CBD). Additionally, Melbourne's tram operating authorities could consider integrating intelligent transportation systems (ITS) to enhance the efficiency of traffic flow at intersections. For example, ITS could be used to dynamically adjust traffic light timings, extending red lights for private cars when there are fewer vehicles, thereby increasing the crossing time for pedestrians and tram passengers, and vice versa. ITS can also provide real-time monitoring of different traffic participants, allowing for immediate response and adjustment in the event of collisions or monitoring traffic flow, pedestrian movement, and tram passenger numbers to reduce the complexity and confusion of mixed traffic. Finally, the Melbourne transportation management department should optimize the design of right-of-way (ROW) regulations, clearly establishing the priority of different traffic participants. Penalties should be imposed on those who violate ROW rules to ensure compliance and improve overall traffic safety.

To enhance the safety of tram drivers, pedestrians, tram passengers, cyclists, and motorcyclists, comprehensive measures must be undertaken. Firstly, it is imperative to strengthen the training programs for tram drivers. These programs should focus on improving drivers' observational skills and their ability to respond promptly to unexpected situations. Emphasis should be placed on maintaining situational awareness and effectively managing the pressures associated with avoiding delays without compromising safety. To ensure adherence to safe driving practices, strict penalties should be imposed for any violations of driving regulations. Furthermore, there should be increased educational efforts targeting pedestrians and tram passengers to raise their awareness of potential dangers and improve their self-protection instincts while participating in traffic. Campaigns should be designed to reduce distractions, such as looking at phones or listening to music, while crossing streets or waiting for trams. Promoting a sense of responsibility and adherence to traffic norms is crucial in ensuring that all road users safely and correctly utilize their designated spaces.

In addition to education, implementing additional safety measures to protect vulnerable road users, such as pedestrians and tram passengers, is essential. This can include better signage, more visible pedestrian crossings, and traffic signals near tram stops. Educational campaigns should highlight the importance of staying alert and following traffic rules to minimize risks. Moreover, fostering a culture of responsible road use among all participants, including cyclists and motorcyclists, is critical. Educational initiatives should inform these groups about the importance of sharing the road safely with trams and other vehicles and the necessity of adhering to traffic regulations. Promoting responsible behavior will help create a safer and more orderly traffic environment. Finally, it is crucial to strengthen the enforcement of traffic regulations, focusing on ensuring that all road users comply with safety norms. Severe penalties should be imposed on drivers who violate regulations, and awareness programs should highlight the importance of traffic safety and the consequences of non-compliance. By adopting these comprehensive measures, the overall safety of Melbourne's mixed-traffic system can be significantly improved, reducing the risk of collisions and ensuring a safer environment for all road users.

5. Conclusion

Melbourne's long history of operating a mixed-traffic system has resulted in frequent collisions between trams and other road users. This paper, using Melbourne as a case study, explored the causes of tram collisions in mixed-traffic environments globally and proposed methods for improvement. From an objective perspective, the arrangement of tram platforms and the design of intersections and right-of-way (ROW) regulations were identified as two primary factors contributing to tram collisions

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in Melbourne. To address these issues, several improvement strategies were recommended. These included establishing elevated tram platforms separated from the road, implementing newer, safer tram station designs, expanding the use of Hook Turn intersections, and integrating intelligent transportation systems. Such measures aimed to mitigate the objective factors leading to tram collisions. From a subjective perspective, tram driver behavior—including situational awareness, time pressure, and organizational behavior—and the actions of passengers, pedestrians, and other road users, such as distractions from mobile phones, contributed to tram collisions. To reduce these human factors, enhancing tram driver training to alleviate stress and providing education for pedestrians and passengers to increase their awareness of traffic risks were effective approaches.

Due to the limitations of the current database, this paper cannot perform more accurate and direct quantitative analyses using firsthand data. Based on the above research and proposed measures, Melbourne's tram mixed traffic situation is expected to improve, helping to reduce tram collisions under mixed traffic conditions, as exemplified by Melbourne. This improvement not only enhances the safety and reliability of tram operations but also contributes to a more efficient and sustainable urban transport system. By addressing both systemic and human factors, the proposed measures aim to create a safer environment for all road users, fostering a more cohesive and cooperative traffic culture.

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