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Review

Virtual reality for fire evacuation from passenger train

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Abstract: Fire safety is an important research area in the rail transportation system. In the event of an emergency, it is important to evacuate railway vehicle in a safe and appropriate manner to minimise injuries and reduce fatalities. Rail companies traditionally conduct full-scale tests. These tests present several drawbacks such as their unrealistic results and their cost-effectiveness. This has led to the necessity of innovating approaches for fire safety training. In this context, new technologies have been employed for evacuation training such as virtual reality (VR). The purpose of this article is to highlight the state of the art of VR simulation of train fire evacuation and examine how VR studies complement conventional research approaches such as drills, laboratory tests and computational models. The findings reveal that VR technologies have great potential for serving as a promising complementary laboratory tool to improve fire safety. Finally, the necessity of new VR researches on passenger train fire evacuation is addressed.

Keywords: fire evacuation, passenger train, virtual reality

INTRODUCTION

In fire safety research emergency evacuation is crucial. Studies of fire incidents show that if individuals are safely evacuated directly after the fire, fatalities can be remarkably reduced. One reason for the inability to rescue occupants on time is that occupants adopt inappropriate evacuation measures due to stress or inexperience with the fire environment. The solution to this issue is to perform emergency evacuation training and drills in a real situation. Nevertheless, on-site drilling has significant drawbacks [1] including cost in terms of time and resources, inability to provide individual feedback on behaviour following an evacuation drill, and being disengaged from the learning process resulting in a restricted change in behaviour.

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Several studies have demonstrated that simulation-based training is a useful method for enhancing user performance in emergency situations while saving trainees from hazards [2]. Among these, virtual reality (VR) has recently received attention in safety training study for fire escape [3]. Despite the increasing number of relevant literature, there are few reviews of VR applications in the area of train evacuation. This investigation intends to address the research gap by performing an analysis of VR simulations of fire passenger train evacuation.

BACKGROUND

What is VR?

VR can be difficult to describe because the term can refer to either a technology or an experience generated by that technology. As a technology, according to Lioce et al. [4], VR is 'The use of computer technology to create an interactive three-dimensional world in which the objects have a sense of spatial presence.' VR as a technology emphasises on technical aspects: image creation, stimulation modelling and interaction. As an experience, VR is the user's perception of being in an environment generated with VR technology. The user is aware that the environment experienced is the result of a specific equipment and is not happening physically [5].

Fire Evacuation in VR

Training is crucial when it comes to safety since it helps trainees become prepared for the actions that are required in stressful situations like emergencies. Previous work in the last five years has revealed a variety of areas where VR safety trainings have been implemented. The review conducted by Feng et al. [1] aimed to understand the implementation of VR-based serious games in the context of building evacuation applied to several indoor emergencies. Nilsson et al. [6] made a prototype of a VR fire evacuation simulator that provided audiovisual information and real-time heat and scent stimulation. Seo et al. [7] conducted a study investigating experiences of VR among young and older adults in a subway fire scenario. Ooi et al. [8] created VR systems for training, firefighting and fire drills that extracted user's behaviour to evaluate the experience and enhance their disaster preparedness. Shaw et al. [9] provided a comparative study examining user's interactions in a virtual fire evacuation from a building and explored how the addition of thermal and olfactory simulation affects this behaviour. Saint Martin et al. [10] summarised the state-of-the-art for VR-based fire evacuation training in hospitals.

Saghafian et al. [11] investigated how the trainees from safety critical industries evaluated the use of VR for fire extinguisher training. Lawson et al. [12] presented the benefits and limitations of using virtual environment training for fire evacuation. Gwynne et al. [2] highlighted the limitations of current evacuation drills and the opportunities provided by emerging technologies to enhance building occupants' safety while minimising the negative effects of drills. De Lama et al. [13] explored an experimental test proposal to study human behaviour in building fire evacuation using virtual environments. Rios and Pelechano [14] carried out VR experiments under different levels of stress in the case of evacuation of a train station. Fu et al. [15] and Wang et al. [16] investigated the impact of fire visibility, fire alarm voices and individual characteristics on occupants' fire evacuation from buildings using a virtual environment. Shiradkar et al. [17] created a virtual university building with several fire safety learning objectives and assessed the training modes empirically. Lorusso et al. [18] presented a methodology for combining a VR platform with numerical simulation tools to reproduce an evolving emergency fire scenario and demonstrated the

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applicability of this methodology to fire evacuation of an existing school building. Kwegyir-Afful [19] investigated the capacity of simulation of a powerhouse's occupants to detect a fire and start an evacuation while performing maintenance tasks. Chen and Chien [20] proposed a fire safety training in high-rise building fire escape based on VR and invited students to explore through this virtual situation.

Despite these studies, few have focused on the application of VR technologies in the railway domain. Thus, in this article we undertake to make a review on train evacuation in the event of a fire.

METHODOLOGY

The methodology is a systematic review of the literature including journals, conference proceedings and industry reports. The study's purpose is to identify the key researches on methods used to investigate train evacuation in the case of fire and then assess them in terms of their strengths, weaknesses, opportunities and threats (SWOT).

The scope definition is stated as the following question: In which contexts do VR simulators for passenger train evacuation become more advantageous than traditional simulations? Databases were searched for articles published between 2012-2022. There were 11 relevant studies. Table 1 presents the list of the included studies, their main topics and conclusions.

Table 1. Articles selected for review process

No.	Title	Ref.	Main topics	Important conclusions
1	A stochastic approach for simulating human behaviour during evacuation process in passenger trains	[21]	- Modelling passenger behaviour during evacuation in passenger trains by providing stochastic model based on Monte Carlo Method - Conducting behavioral comparison for evaluation of impact of passenger actions in predicted evacuation times	"Specific characteristics of passenger trains restrict the use of currently available evacuation models." "Stochastic model permits representation of the random character of evacuation processes." "More behavioral factors should be included in evacuation analysis and new approaches should be done to obtain reliable and accurate results."

Table 1. (Continued)

No.	Title	Ref.	Main topics	Important conclusions
2	Analysis of evacuation procedures in high speed trains fires	[22]	Examination of different evacuation strategies for two high-speed trains using computer simulation	"Computer modelling analyses could improve evacuation procedures under various conditions." "Data collection results suggest that default values in current egress models (mostly designed for buildings) may not be adequate for trains." "In real emergencies passengers may be more motivated to escape than they are in evacuation drill."
3	A new approach for modelling passenger trains evacuation procedures	[23]	Proposition of new model for simulating and investigating results of various evacuation procedures in passenger trains	"Model user can explore different evacuation processes by changing basic input parameters." "Proposed model generates and processes results within a few seconds."
4	Simulation research on human evacuation in subway with a single-point fire scenario	[24]	Simulation research of subway evacuation focusing on smoke diffusion throughout tunnel and cars	"Simultaneous fire and evacuation simulation via evacuation module may be more objective and comprehensive. More reliable theories for some emergency and evacuation plans may be proposed."
5	Fire safety assessment of open wide gangway underground trains in tunnels using coupled fire and evacuation simulation	[25]	Evaluation of fire safety performance offered by conventional train configuration and new configuration through numerical simulations	"There are many possible scenarios that can be examined in any numerical simulation of complex process." "This model is used to successfully simulate fire spread in several real fire cases/experiments."

Table 1. (Continued)

No.	Title	Ref.	Main topics	Important conclusions
6	Human behaviour in emergency situations: Comparisons between aviation and rail domains	[26]	Providing comparative analysis of existing knowledge in aviation and rail about human behaviour in emergency situations	"Computer simulations provide safe method of testing emergency evacuations without need to recruit participants." "Degree of accuracy in computer simulations is still contentious due to lack of available emergency evacuation data." "There are limitations on use of full-scale trials."
7	Virtual and augmented reality and gamification as training tools in safety critical industries	[27]	Evaluation of benefits of VR in context of safety critical training for rail sector	"VR technology permits complex, risk-filled and rare scenarios to be reproduced in highly accurate, replicable, safe and low-cost manner."
8	Experimental study on occupant evacuation in narrow-seat aisle	[28]	Conducting experiments to simulate passenger evacuation in narrow-seat aisle and evaluating occupant evacuation behaviours	"Study gives a useful standard for evacuation simulation of narrow-seat aisle as well as reference to safety design of seat area in train cars."
9	Passengers' evacuation from a fire train in railway tunnel	[29]	Calculation of average evacuation speed and time for young adults in event of train fire in railway tunnel using numerical simulations and experiments	"Numerical simulation is reliable tool for simulating passengers' evacuation from fire train." "Experimental results are in good accordance with numerical simulation results." "Factors such as behaviour characteristics of people remain to be determined."

Table 1. (Continued)

No.	Title	Ref.	Main topics	Important conclusions
10	Evaluating the potential for virtual reality, augmented reality and gamification in rail industry safety critical training	[30]	Providing recommendations to rail sector on when and how to adopt immersive technology to improve critical safety-related training, as well as important principles for successful implementation	"Training using immersive technology is generally received well by learners and results in high levels of engagement. Learners are more likely to retain information than when using traditional 'chalk and talk' methods, and to change attitudes and behaviours towards learning." "Immersive technology allows trainers to accurately repeat training scenarios for specific learning output, a variable which cannot always be controlled in a real environment."
11	Evacuation trials from a double-deck electric train unit: Experimental data and sensitivity analysis	[31]	Developing simulation model of evacuation based on experimental study that involved full-scale controlled evacuation from railcar	"Experimental set-up was designed in controlled environment. Despite its advantages, this data collection method cannot fully reflect real-life situations." "Limitations associated with lack of contextual realism, limited capacity for simulating more evacuation scenarios, and presence of training effect must be considered."

ANALYSIS

This section seeks to summarise important findings from the completed included studies. Each study was closely examined to compare between the application of conventional methods for train fire evacuation and the VR simulation by using SWOT analysis. Table 2 presents an overview of SWOT findings of VR for fire evacuation research. Table 3 compares four research methods used to study train evacuation in the case of fire and evaluates these methods regarding each aspect listed in Table 2.

Table 2. Overview of SWOT findings for research using VR in train fire evacuation

Strength	**Weakness**
Controlled environment **Safety** **Replicability** **Flexibility** **Low costs**	Experimental validation Technical limitations Simulator sickness
Opportunity	**Threat**
Scientific opportunities **Multi-sensor simulations** **Interoperability**	Medical side effects Misleading expectations Full validity

Table 3. Comparisons of methods used in train fire evacuation research

	SWOT VR technology	**Drill**	**Laboratory experiment**	**Computational simulation tool**
Strength	Controlled environment	No	Low	High
	Safety	Low	Medium	High
	Replicability	No	Yes	Yes
	Flexibility	No	Yes	Yes
	Low costs	No	Yes	Yes
Weakness	Experimental validation	High	Medium	Low
	Technical limitations	Low	Low	Medium
	Simulator sickness	No	No	No
Opportunity	Scientific opportunities	Low	Low	High
	Multi-sensor simulations	High	High	Low
	Interoperability	No	No	Yes
Threat	Full validity	No	No	Yes
	Misleading expectations	No	No	Yes
	Medical side effects	No	No	No

The SWOT analysis shows that VR's greatest strengths over other methods are its capacity to create a highly controlled environment since studies can be conducted in a safe laboratory environment. Controlling the environment in drills and even laboratory experiments is extremely difficult. For example, real smoke will always vary, even in the controlled environment of a classical laboratory study, and as a result, visibility conditions may vary across observations. Smoke, on the other hand, can be numerically calculated and then shown in exactly the same way in VR and computational simulation. VR also offers a safe environment for experiments under high-risk situations without risking physical harm. Catastrophic scenarios can be simulated without any risk.

With VR, experimental parameters can be modified and replicated easily. Drills provide data for only one specific event using the same methods with the same participants. Laboratory experiments and computational simulation offer the possibility to implement adjustments during investigation and repeat the same scenario with different participants. VR is also affordable once a VR system is installed. The enormous series of training scenarios raises the training cost. As drills cannot perform all of these training scenarios in the same location and with the same equipment, VR, computer simulation and laboratory experiments are generally less expensive than drills. Furthermore, users can complete the investigation without compromising the operation of the railway line.

The following, however, are the most prevalent weaknesses of VR. In the first place, there have not been enough experimental validation of VR studies conducted to date. The efficacy of VR findings can only be demonstrated if they are comparable to what would be envisaged in a real situation. Drills and laboratory experiments are evaluated as the model with the highest similarity to the real world. In turn, drill data are frequently used to create and calibrate computational simulations. As a result, the failure to prove its validity is the major problem of VR as a research tool.

In the second place, technical limitations with VR technology, such as the quality of the visual, the motion response speed , restricted field of image, low contrast and resolution, reduce the immersion of a VR system and the sense of presence [27]. Users must be conscious of such constraints in order to avoid false expectations. This is essential when introducing new technologies to the rail industry to prevent disappointing the railway companies and causing them to lose confidence in a technology with enormous potential.

Lastly, simulator sickness is a significant weakness of VR technology since it is frequently mentioned by users who take part in VR studies [27]. For individuals with pre-existing medical issues, caution is required to prevent the appearance of medical side effects. In addition to the motion sickness mentioned, VR can cause specific phobias (of enclosed spaces, heights, etc.). The issue of medical side effects does not apply to other methods.

As for the topic of opportunities, the VR technologies open up new horizons for researchers, such as relatively affordable equipment, open-source codes for programming and use of existing applications for future research in the field of train passenger evacuation. Similar opportunities apply to numerical simulations. However, the scientific potential for other methods is limited and is based on the development of new technologies.

Interoperability presupposes that researchers can easily share 3D models or even entire experiments with one another. This could encourage collaboration among laboratories and lead to the creation of predefined scenarios that could serve as a guide for various VR and computer simulation investigations. This opportunity is not offered for drills and laboratory experiments.

Multi-sensor simulations offer the chance to include multi-modal simulations for tactile, olfactory, haptic and thermoceptive effects in addition to visual and audio simulation. The addition of these sensors is very useful to improve the quality of the simulation results. For example, the addition of a heat sensor as part of the study of fire evacuation procedures could better approximate the VR simulation to the real environment. Drills and laboratory experiments already have this opportunity as one of their strengths. However, for numerical simulations, this opportunity still remains a weakness.

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CONCLUSIONS

VR technology has the potential to improve the train evacuation training in the event of fire and to serve as a complementary tool for other modes of evacuation training. It should be noted, however, that there is still much to be done in this domain, and without adequate user studies that use real data and VR simulations adapted to the field of train evacuation, there is limited knowledge concerning the effectiveness of this technology in helping to improve fire safety in trains.

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