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Integrating Virtual Reality and Building Information Modeling for Improving Highway Tunnel Emergency Response Training

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Abstract: During the last two decades, managers have been applying Building Information Modeling (BIM) to improve the quality of management as well as operation. The effectiveness of applications within a BIM environment is restrained by the limited immersive experience in virtual environments. Defined as the immersive visualization of virtual scenes, Virtual Reality (VR) is an emerging technology that can be actively explored to expand BIM to more usage. This paper highlights the need for a structured methodology for the integration of BIM/VR and gives a generic review of BIM and VR in training platforms for management in infrastructures. The rationales for fire evacuation training were formed based on the review. Then, methods of configuring BIM + VR prototypes were formulated for emergency response in highway tunnels. Furthermore, a conceptual framework integrating BIM with VR was proposed to enable the visualization of the physical context in real-time during the training. The result indicated that, extended to the training system of highway management via the "hand" of BIM, the VR solution can benefit more areas, such as the cost of fire evacuation drills in highway tunnels and the tendency of accidents to occur in the emergency response.

Keywords: BIM; VR; emergency response; training system of highway management

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1. Introduction

With the rapid development of the social economy, coupled with the breakthrough of building technology, buildings are developing towards high-rise and large-scale, which brings a new challenge to fire safety [1]. In the last five years, there were 1,423,000 fires in China, causing 142,000 casualties. By the end of 2020, China had built 21,316 road tunnels with a total length of 21,999.3 km, of which 1394 are super long tunnels with a length of 6235.5 km, and 5541 are long tunnels with a length of 9633.2 km [2,3]. Highway tunnels are large-scale infrastructures with high interspace and management complexity [4–6]. The poor operation conditions such as the hydro-geological uncertainty in mountainous areas increase the complexity of the facility management in highway tunnels compared with buildings. Tunnels' characteristics of a narrow and semi-closed structure make fire evacuation a crucial work. Moreover, dangerous goods transport vehicles increase the risks of the evacuation process in a tunnel fire. Once a fire accident occurs, the fire smoke is difficult to discharge. In addition, it is difficult for the rescue force to enter quickly, which easily causes mass casualties. Thus, a skilled evacuation process and proper responses play an important role in increasing the safety and survival chance in an emergency.

Traditional emergency management employs skill courses and evacuation drills to enhance emergency planning. However, it consumes a large amount of manpower and resources while in this kind of exercise, it is difficult to simulate the actual fire scene during the training process. Moreover, the traditional approaches exhibit some limitations on knowledge transmitting, training assessment, and planning optimization. Before the evacuation drill, videos, seminars, and courses cannot attract trainees' attention resulting in little enhancement in survival awareness and limited change in behavior [7]. During the drill, participants spend a lot of time but get no individual feedback from the assessment system [8]. After the drill, the following modification process to address fire emergency issues would be very time-consuming and costly. Therefore, a virtual training tool that supports immersing experience, transmitting professional knowledge, and simulating multiple scenarios is in great demand in the safety management of tunnels.

Currently, Building Information Modeling (BIM) technology boosts the smart and efficient management for whole life cycle management on infrastructures. Three-dimensional visualization and the information management mechanisms in BIM enable specialists from different disciplines to work in one joint and rich data model. To visualize the 3D model, some viewers provide stereoscopic visualization to be used for Virtual Reality (VR) environments such as the Oculus Rift. In practice, VR is regarded as an extended application of BIM, conveying BIM into the daily management of infrastructures. In the design phase, the immerse environment based on VR and BIM could facilitate communication and then reduce the re-design and rework. During the construction phase, the usual manual workspace planning process could be enhanced by a BIM-based VR approach by simulating a real-scale virtual construction activity [9–11]. The cost and efficiency of facility management (FM) have also been optimized by the BIM-based VR environment tool. For example, Shi et al. [12] developed a multiuser shared immersive virtual environment to bring remotely located stakeholders—building occupants, facility managers, vendors, and designers—together to walk through the same virtual building. VR can also help FM personnel visualize facilities in detail before conducting an actual visit to the site using a BIM model [13–15]. Integrated with the game engine and BIM, VR applications have been developed for facilitating design, visualization, management, and communication in AEC/FM industry. Specifically, construction safety education could also be enhanced by increasing safety awareness and simulating the construction process in the virtual environment [16]. Froehlich et al. [17] introduced 3D VR headsets in construction for safety training and found the great potential of VR for safety education. Therefore, a safety training platform could be developed based on the precise reconstruction of structures from BIM and immersing scenarios from VR.

Tunnel emergency response training in this paper will take advantage of current studies and address some limitations in current research. According to the review on VR evacuation training, 11 of the 15 reviewed papers focused on fire evacuation [18]. Pedestrian evacuation behavior under varying visibility has been extensively studied through artificial smoke in the virtual environment [19,20]. Integrated with BIM, an accurate building geometry could be displayed at a low cost and enhance the immersed experience. However, the information interaction between BIM and VR needs to be enhanced. Sidani et al. [21] pointed out that the potential of BIM should be explored further but most VR interfaces do not possess a database component to provide access to BIM parametric information. Moreover, the integration in safety training faces additional costs for developing the platform and the non-availability of safety elements and equipment in the BIM/VR software library. Thus, cost and immersive experience shall be considered comprehensively in the choice of the operational hardware and the development of the virtual environment. Moreover, most simulation applications were developed in laboratories for very specific contexts of use but have not been tested in real projects [22–24]. Prototype systems should be optimized by professionals and site superintendents to be translated into real-life training. Lastly, modes of real-time instruction and non-instruction will be designed to check the effect of the training and provide individual feedback to participants.

In this paper, VR based on BIM will be investigated to develop solutions for a highway tunnel to facilitate the efficiency of emergency response. Recent advances in hardware capability have boosted BIM + VR to provide an effective validation of the proposed processing flow and vivid experience of emergency response. VR will be employed to visualize facilities in the tunnel and operation center to enable participants to experience the emergency response process flow while the real workspace of the modeled tunnel is narrow. A platform has been specified and prototyped in this study, partially demonstrating the performance of BIM + VR for simulating emergency situations, training staff, and the tunnel users. Specifically, VR device Oculus Quest linked with a high-performance computer are used as the platform to enable the BIM + VR platform. Most emergency response activities can be realized by this platform, including fire evacuation process flow to the highway system front staff, center operation process flow to the operators in the operation center, and fire evacuation process to the tunnel users.

2. Literature Review

BIM and VR have attracted great attention in the field of Construction 4.0. Boton et al. [25] found that BIM was the most mentioned keyword, followed by augmented reality (AR) and virtual reality (VR). Specifically, AR is more employed in the preconstruction phase and related to the technical task mapping. VR is usually utilized in ensuring construction safety and enhancing skill training. BIM and VR are reasonable and feasible technologies for developing the training platform with the great potential for visualization and smart buildings. Thus, a training platform integrating BIM and VR technology is the focus of this research.

Drills in a virtual environment will transmit the knowledge to trainees, record their behavior, and provide individual feedback coving comprehensive aspects. BIM has exhibited great potential in structure visualization, cross-departmental communication, and workplace planning [26]. In recent years, the application of BIM in the nD environment has been actively explored in the field of workplace planning, facility management, and smart infrastructures [27–29]. More engineering analyses and business functions have been developed on BIM, which is moving away from merely 3D modeling for drawings [30,31]. BIM has been developed in building performance assessment to secure the calculation of energy balances and result in higher flexibility in optimizing a building design [32,33]. Similarly, BIM expands the applications in fire prevention and disaster relief due to the characteristic of the visualization tool and analysis tool. Cheng et al. [34] proposed an intelligent fire disaster prevention system by integrating BIM and Bluetooth. The BIM-based system provides 3D visualization to support the assessment and planning of fire safety to direct the efficient evacuation. The integration of BIM and sensor networks introduces a novel approach for fire monitoring and evacuating decision-making [35–37]. However, this system cannot meet the demand of the training plan in a tunnel. Visibility has a great impact on escape chances due to the semi-closed structure of tunnels. Single BIM technology cannot simulate the effect of smoke/temperature/cracking sounds in real fires on emergency procedures [38–40]. Moreover, a necessary function of the training platform is to facilitate the trainees perceiving the environment and making the correct decisions when their visibility is compromised. Therefore, more exploration of "BIM +" is urgent to provide a complete and realistic training platform for emergency response.

Emergency drill systems should consider the interaction between the virtual environment and trainees. The powerful value of BIM-based game engines in creating a low-cost and realistic game environment has been widely recognized. Rüppel et al. [41] utilized a physics engine to develop immerse scenarios in a BIM-based serious game for fire safety evacuation simulations. The integrated physics engine, such as Nvidia-PhysX, can qualitatively simulate fire and smoke as well as structural damage after explosions. Similarly, Li et al. [1] proposed a novel approach to realize fire dynamic simulation and evacuation optimization. Focusing on the inducing factors and spread, a fire source heat release rate and combustion model is established based on the technology of BIM and Pyrosim. Therefore, the simulation of traffic accident, fire, and smoke are feasible in the emergency response training platform [42,43]. Pedestrian evacuation behavior under varying visibility has been extensively studied through artificial smoke in the virtual environment [20,44,45]. However, BIM just works as a location and visualization tool but cannot interact with participants. Facilities such as emergency phones, escape routes, and fire extinguishers must operate the same as in a real-world environment to enhance the immersive experience.

VR is regarded as an extended application of BIM, conveying BIM into the daily management of infrastructures. With the current advancement of VR technologies, the integration of BIM-based game engines and VR is becoming promising in the AEC industry, particularly in safety training. Unlike BIM-based game engines, VR allows participants to interact with the environment and other users. VR has been extensively investigated to simulate emergencies such as fire events, traffic accidents, earthquakes, etc. Safety education could also be enhanced by increasing safety awareness and simulating the construction process in the virtual environment [16,46]. Froehlich et al. [17] utilized the Oculus® DK2 VR headset to visit the virtual Jobsite and identified safety hazards. Feedback from participants shows that safety training may be the best candidate for VR applications. The ability to interact with all the objects in the game is still limited, though the immersed environment is developed. Thus, Lamberti et al. [47] enhanced the operability of a tunnel fire simulator with multi-role and multi-user capacity. For example, extinguishers, once grabbed, require further interaction with the other hand to take the safety off. Then, the content can be sprayed by pressing a second button. A similar operation will be further expanded in our research such as the broken window hammer, safe entrance gate, finding fire source, etc. Moreover, the roles and users in the training will also be further increased beyond the car driver, passenger, truck driver, and two firefighters. Lastly, modes of real-time instruction and non-instruction will be designed to check the effect of the training and provide individual feedback to participants.

The scenarios of the tunnel emergency response in the training platform are related to the cost and professional knowledge. The virtual environment must reconstruct the task demands and stressors that trainees experienced in reality to be deemed effective. The design of these exercises must be well thought out in advance. Moreover, cost and immersive experience shall be considered comprehensively in the choice of the operational hardware and the development of the virtual environment. One desired goal of a training platform is to generate expected training outcomes most cost-effectively. Therefore, the most necessary and appropriate details of the simulation will be reproduced in the virtual environment [48,49]. Most research demonstrated that BIM had the potential to display fire information and evacuation routes [50–52]. The comprehensive and standardized data format and the integrated process will provide real-time and accurate building information under an emergency situation. Wang et al. [53] researched the seamless integration of BIM/VR in a serious game for providing real-time guidance in a fire evacuation. Similarly, Chen et al. [38] proposed an integrated framework containing innovative technologies including BIM, the Internet of Things, and AR/VR systems to ameliorate the level of situational awareness. However, most simulation applications were developed in laboratories for very specific contexts of use but have not been tested in real projects [22,54]. Prototype systems should be optimized by professionals and site superintendents to be translated into real-life training.

3. Methods

This research was initiated by Jiangxi Provincial Communications Investment Group Co., Ltd., Nanchang, China and was jointly performed by East China Jiao Tong University and Curtin University. The project aims to develop a simulation training platform to enhance the skills and optimize the existing plans for handling emergency response. The research gap from the literature review will be considered in proposing and validating the platform. The overall architecture goes through four stages successively: from physical to digital, the BIM asset will be developed from the 3D Geometry CAD model; from digital to virtual, BIM data will be processed in a VR environment and further VR interaction in Unity will complete the VR training sceneries; and finally, from virtual to physical, plans and skills to handle the emergency scenarios in real tunnels will be optimized through the

VR training. Development of the platform is divided into seven major phases including "Process BIM asset", "Prepare BIM data", "Optimize mesh for VR", "Simulate and render", "VR interaction", "Training scenery in VR", and "Immersive training experience in VR" (Figure 1). The first four phases aim to complete the environment simulating. The model and material in BIM will be processed for VR and then the scene will be rendered in the phase "Simulate and render". Next, "VR interaction" utilizes the Oculus Rift to add VR support for the target device, create internal movement interaction for FPP, and create an internal movement of FPS for a stationary VR experience. Then, multi-roles training content and multi-scenes in VR experience are the focus of the "Training scenery in VR". Lastly, "Training scenery in VR" generates real-time instruction mode and without instruction mode in the platform for teaching the training skills and evaluating the training effect. More details of the seven phases are illustrated as follows:

- Process BIM asset
  (1) Configuration of BIM asset in Revit, group family type objects and configure unique ID for each mesh object.
  (2) Selecting a view with all the elements that need to be exported.
  (3) Clear non-BIM entities such as camera, light source, and section box.
  (4) Export elements into FBX format that contains mesh data.
  (5) Export elements into JSON format that contains material information and building information.
  (6) Export mesh and data link into XML format so the mesh object and building information can be mapped.
  (7) Export plans (sites floor plane) into 1:1 vector scale using metric system for reference.
- Prepare BIM data
  (1) Load FBX mesh data into Blender.
  (2) Re-configure the coordinate system by setup the default world anchor.
  (3) Group mesh elements into a spatial hierarchy.
  (4) Convert non-Revit documents information into JSON or XML.
- Optimize mesh for VR
  (1) Reduce triangle by re-meshing object, especially the cylinder.
  (2) Remove double vertex.
  (3) Filter and remove annotation mesh objects such as 3D texts and indications.
  (4) Relocation double plane to avoid z-index flight.
  (5) Calculated inside and outside normal.
  (6) Draw double side UV for non-solidified object such as plane and material layers.
  (7) Create level of detail for complex objects.
  (8) Create/convert to PBR materials for outer layer of the object based on BIM material information.
  (9) Unwrap the UV for all the elements for texturing.
  (10) Export the model and material into OBJ format.
- Simulate and render
  (1) Import OBJ into Unity.
  (2) Revaluate the UV layer for lights information.
  (3) Set up globes illumination information such as directional lights and skybox.
  (4) Set up light reflection probes lone the path of the road in the mesh data.
  (5) Before rendering the scene, add extra environments details such as plants if needed.
  (6) Bake the lighting of the scene to complete the environment simulation.
- VR interaction
  (1) In Unity, add VR support for a target device, in this project, the Oculus Rift.

(2) Add walkable area by adding floor colliders base on the BIM, filter the road surface and add the mesh colliders into the element.
(3) Create internal movement interaction for FPP, a free roam VR experience requires a larger space for the user to walk around, and set up a boundary box to map the physical space to alert the user of approaching the edge of the space.
(4) Create an internal movement of FPS using the teleporting method for a stationary VR experience.
(5) Create object interactions based on the training procedures.
(6) Interaction with tools (build based on the Safety Equipment documents) to use in the scene via gestures (pickup, holding, pointing, and releasing):
    (a) Edit sound effects to give feedback on the status while interacting with objects.
    (b) Program controller vibration (intensity and frequency) to simulate the feedback of power tools used in the training process.
    (c) Created VFX to simulate the result of using the tool on different materials.
(7) Create an immersive menu for document base information display by simulating the clipboard in VR (turning pages).

- Training scenery in VR
    (1) Create a scenery storyline based on training documents and safety instructions.
    (2) Extract objectives of the training process and divide them into sections.
    (3) Build sceneries script and event system in Unity for each section.
    (4) Generate procedure training sceneries by connecting sections and their objectives.
- Build training experience in VR
    (1) Generate emergency response planning procedures with instruction, each section will provide the user with a clear objective, visual and sound instructions, and path guidance. In this training mode, the user can follow the instruction to complete the emergency planning procedures.
    (2) Generate emergency response planning procedures without instruction. Each section will provide the user with only the status update of the event, the user can complete tasks with its knowledge to achieve the objectives. The event is timed so the user can review the result of each section.

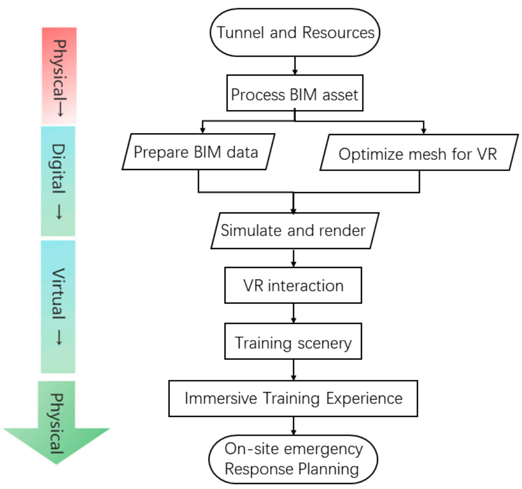


Figure 1. Development workflow of the training platform.

4. BIM + VR Training Platform

The development and employment of an integration platform of BIM and VR are illustrated in the following sub-sections. The proposed BIM + VR applications in the emergency response of highway tunnels will be demonstrated via a real project. The conceptual diagram for the platform architecture is shown in Figure 2, which integrates the 3D BIM design, virtual reality, and the real emergency response training plans. First of all, the BIM model was developed from the 3D Geometry CAD model to virtualize the tunnel with information about the structure and affiliated emergency facilities. The construction materials, safety equipment, safety instructions, and schedules were integrated into the virtual environment for the training. Thereafter, the model elements in the BIM model would be linked to VR visualization, and the interaction would be realized between participants and facilities such as cameras, monitoring rooms, broadcasts, fire extinguishers, etc. (Figure 3). Two models of this platform were designed for the monitoring room and the tunnel emergency response training, respectively. Moreover, three systems were simulated for the emergency response teams, dangerous goods truck drivers, and coach passengers in the training. Prompt boxes (represented by VR), flashing lights, and broadcasts were employed in the platform to navigate participants through the training. The visual tips and broadcasts would reduce the time for locating and guiding the rescue.

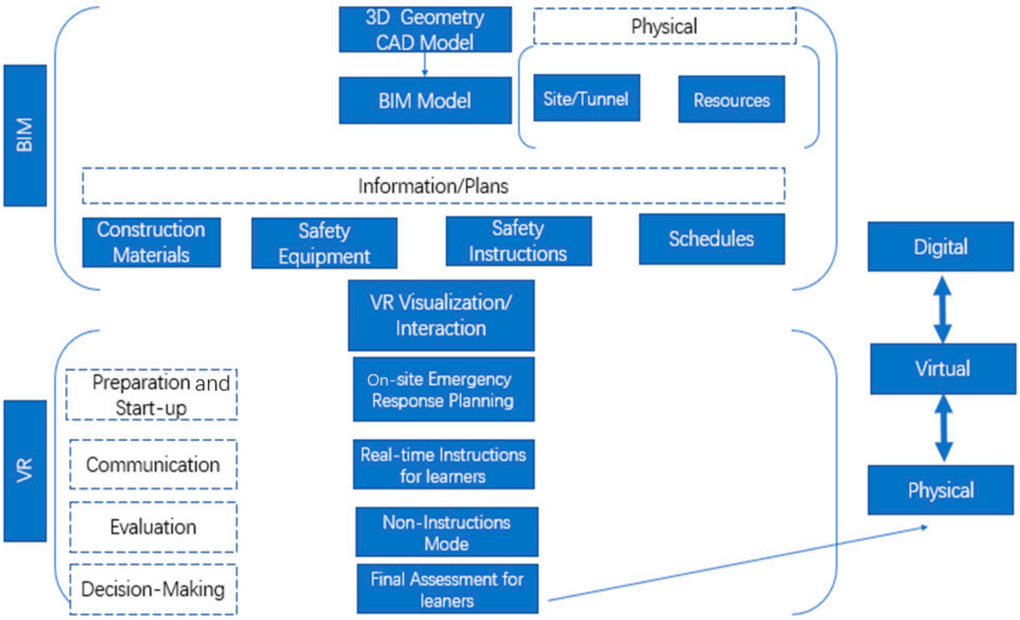


Figure 2. Integration of BIM and VR for emergency response training in highway tunnels.

(**a**) (**b**)

Figure 3. The trainee equipped with VR hardware in (**a**) showroom and (**b**) training room.

Modes of real-time instruction and non-instruction were designed to check the effect of the immerse training. In emergency response, frontline emergency personnel must form accurate spatial working memory with limited time in an unfamiliar environment. Therefore, users could familiarize themselves with the operating procedures in the mode of real-time instructions until they could complete the rescue mission within the specified time. Then, users could participate in the emergency response training in the mode of non-instructions. The development of flames and smoke were simulated in the VR environment to bring stress and anxiety to trainees. Realistic simulation in the immersive environment will provide trainees with adequate experience to cope with a similar situation in an actual task. Finally, the platform will generate a final assessment for learners to promote their grasp of the emergency response procedure.

4.1. Training System 1: For the Operator in the Central Control Room

This system consists of monitoring screens, central control system, and an introduction sheet with a mass of regulations and guidelines for tunnel management and emergency response. Using VR, trainees can effectively assess emergency situations and handling procedures. Essentially, VR involves human sensations with virtual information sources. VR can enable interactive functionality and immersive visualization that facilitate the study and training. In practice, most training is realized via PPT, 2D facts sheets, and videos from real environments and animation. However, lots of text introductions and drawings make the traditional training method inefficient and not intuitive, even negatively impacting the trainees who get tired of reading study materials. A more reliable and comprehensive method than written exams has been expected to assess trainees in the study and training. In practice, a VR training system can track the steps of operation and set time limits for each session. Thus, a long-term training system containing handling procedures and schedule performance was developed to improve the assessment of the training. This VR platform provided operators with a 3D interactive environment of the central control room for a visual understanding of details in the rescue process (Figure 4).

Figure 4. Training System 1: for the operators in the central control room.

Operators could review the accident that occurred in highway tunnels and search the corresponding handling procedures in the VR environment. The central control room can provide timely and correct assistance to multi-role trainees in subsequent drills. This VR system provides three common emergency scenarios for operators:

1. Illegal stop in the tunnel
2. Car crash in the tunnel
3. Heavy fire occurs in the tunnels

The operators in the virtual control room could check the computer for detailed information in each scenario and look around for instruction tips as well (Figure 5). A high level of immersive study was achieved and conveyed clearly to the trainees through

VR facilities. Moreover, when the virtual control room was created, unlimited training scripts could be linked to the virtual world so that the operator would use the VR hardware to study the evacuation program. Additionally, the manager could assess and monitor trainees to find the potential defects when emergency situations occurred in the tunnel.

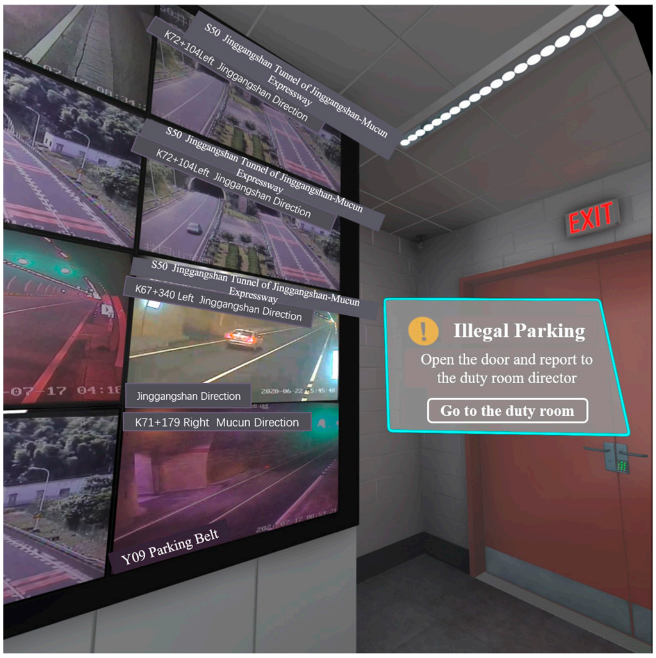
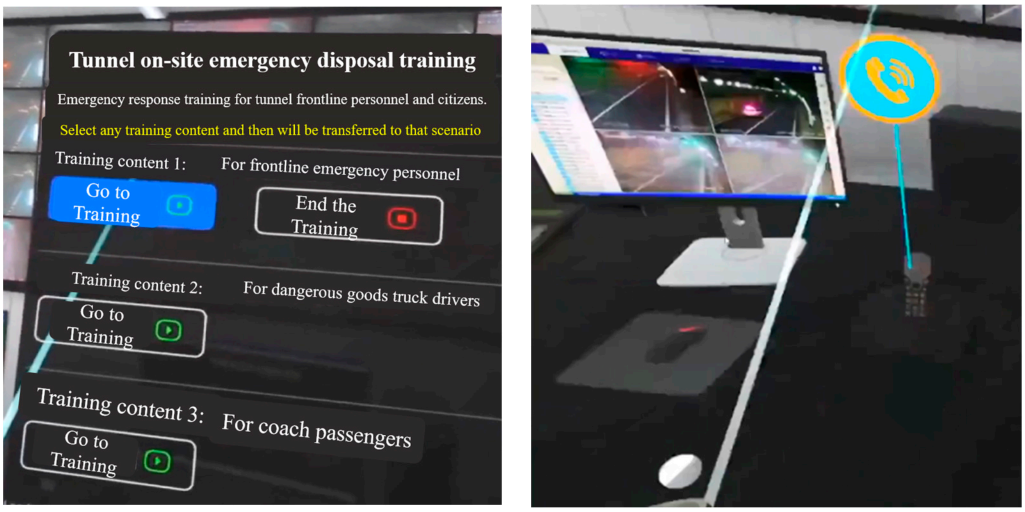


Figure 5. An illegal stop in the tunnel and related handling procedure tips.

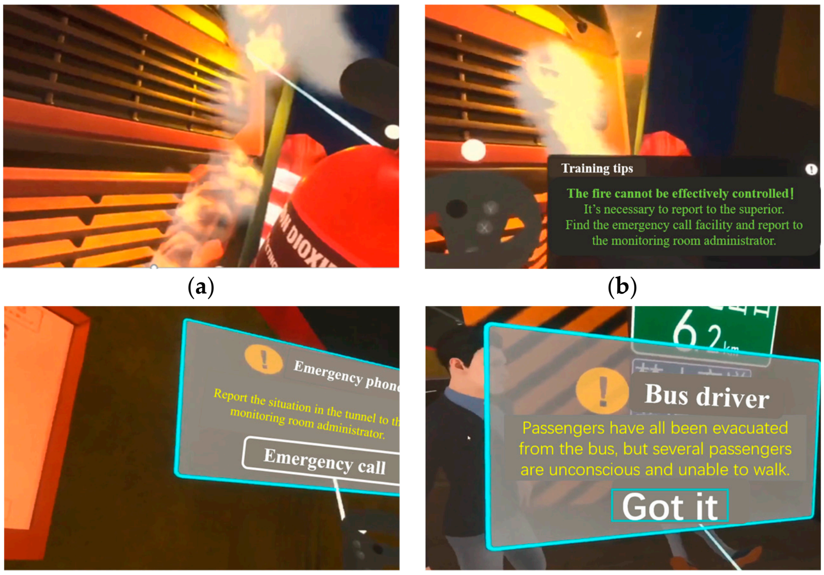
4.2. Training System 2: For Emergency Response Group

The emergency response group could select the first system in the menu (Figure 6). Safe evacuation mainly relies on accident lighting and evacuation indication signs when a fire breaks out in the tunnel. The large smoke concentration and low visibility may seriously affect the evacuation speed since panicked escapees cannot distinguish the direction. Furthermore, evacuation of personnel and materials are also limited by the small cross-section of the tunnel and the small emergency exit. First of all, the control room receives an emergency call from the drivers and passengers in the tunnel about a fire accident. The location and severity of the emergency could be obtained from the screen of the monitoring center. Then, the group will set off and the broadcast will guide the drivers and passengers to the rescue channels. The emergency truck would place warning signs at the tunnel entrance and evacuate the blocked vehicles in the tunnel. The group would be helped by the VR tips to search the fire and locate fire extinguishers. The operation of a fire hose needs at least two people, one takes out the water belt and does other preparatory work, and the other one waited to open the water valve and regulate the jet (Figure 7). When the fire is uncontrollable or civilians are in a coma, there will be a prompt box to remind the emergency personnel to find an emergency call facility to report to the monitoring administrator and superiors (Figure 7). Meanwhile, operators in the central control room will connect with the emergency response group and provide support. The broadcast and emergency calls in the system could improve the cooperation between the front-line rescue team and the central control room. Through the immersive experience of VR, the emergency response group can deal more calmly with smoke and flames when responding to emergencies in reality.



(**a**) (**b**)

Figure 6. Training System 2: for the staff in the central control room. (**a**) The main menu of the training system; (**b**) Motion cues during training.



(**a**) (**b**)

(**c**) (**d**)

Figure 7. Training System 2: for the emergency response group. (**a**) The group could use a fire extinguisher to extinguish the fire; (**b**) Training tips that fires cannot be effectively controlled; (**c**) Emergency phone tips; (**d**) Learn about the scene from the car driver.

4.3. Training System 3: For Dangerous Goods Truck Driver

Dangerous goods transporters will increase the risks of emergencies due to the closed structural space of the tunnel. The special structure of the tunnel cannot accommodate too many personnel and equipment entering the tunnel at the same time. In addition, the operating space of the rescue group is also limited. Two-way traffic tunnels and long tunnels are prone to cross rescue routes, evacuation routes, and flue gas flow routes [55–58]. The drivers need to be familiar with the emergency response procedure. An emergency scenario was conducted for the drivers when they drive in the tunnel and prompt boxes represented by VR will warn the drivers about the emergency such as punctures and burning (Figure 8). Then, the real-time instruction for the emergency response will be represented in the VR environment, including turning on the dual flash and pulling up the brakes. Another prompt box will inform the driver that the front line is on fire and the emergency call facility and the firefighting facility need to be found within the specified time, otherwise the fire will spread rapidly. In addition, the sign of emergency facilities will be displayed via VR using bright colors to guide the driver. First, the driver should report to the monitoring room about the location of the fire, the type of cargo loaded, and the time of occurrence. Then, the driver could find the firefighting facility next to the emergency call facility to extinguish the fire. The correct way is also required in the use of fire extinguishers similar to the training system for the emergency response group. The assessment module also displays whether or not the user maintained a safe distance with the car, used the emergency call facility, used the extinguisher on the fire, completed the procedure at the specific time, etc.

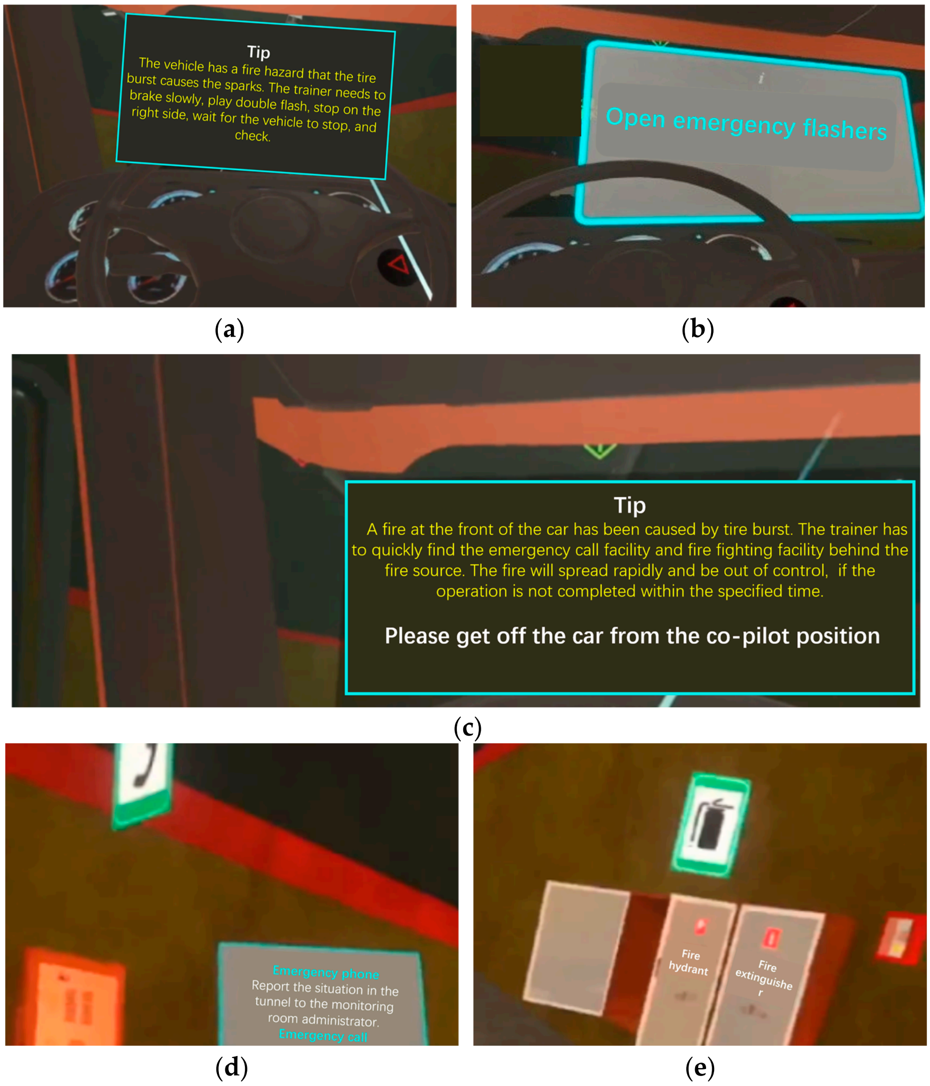


Figure 8. Training System 3: for dangerous goods truck driver. (**a**) The driver receives a tip about a fire hazard of the vehicle; (**b**) Instructions will direct the driver to conduct the emergency response; (**c**) Tip could help the driver locate the fire and be familiar with the response process; Tips for locating the emergency phone (**d**) and fire hydrant (**e**).

Through the immersive experience of VR, drivers can deal more calmly with smoke and flames when responding to emergencies in reality. The emotional panic caused by alarms and others helps drivers and passengers save first aid time, better protect life safety, and reduce property damage.

4.4. Training System 4: For Coach Passengers

This system is designed for coach passengers to escape from the coach and the tunnel. An emergency scenario was simulated for the passengers when an accident occurs on a coach in Figure 9. Temperature and soot spread rapidly due to thermodynamic effects when a fire breaks out in the tunnel. Car tires and fuel tank fuel are flammable and will also increase the intensity of combustion. After the mechanical smoke extraction facility is activated, the flow of high-temperature flue gases is accelerated, which also provides conditions for the spread of fire. Prompts from broadcast and VR simultaneously guide passengers to escape from the coach. Passengers will use a broken window hammer to break glass and use clothing to avoid scratches on their hands when escaping through windows. The sign of emergency facilities will be displayed via VR using bright colors to guide the passengers. They should tell the monitoring room about the location of the accident and the time of occurrence. Moreover, passengers could find the firefighting facility next to the emergency call facility if the accident leads to a fire. The VR prompt box will guide passengers to the evacuation channel closest to the scene of the incident. Finally, passengers can open the escape tunnel and the emergency response training is over.

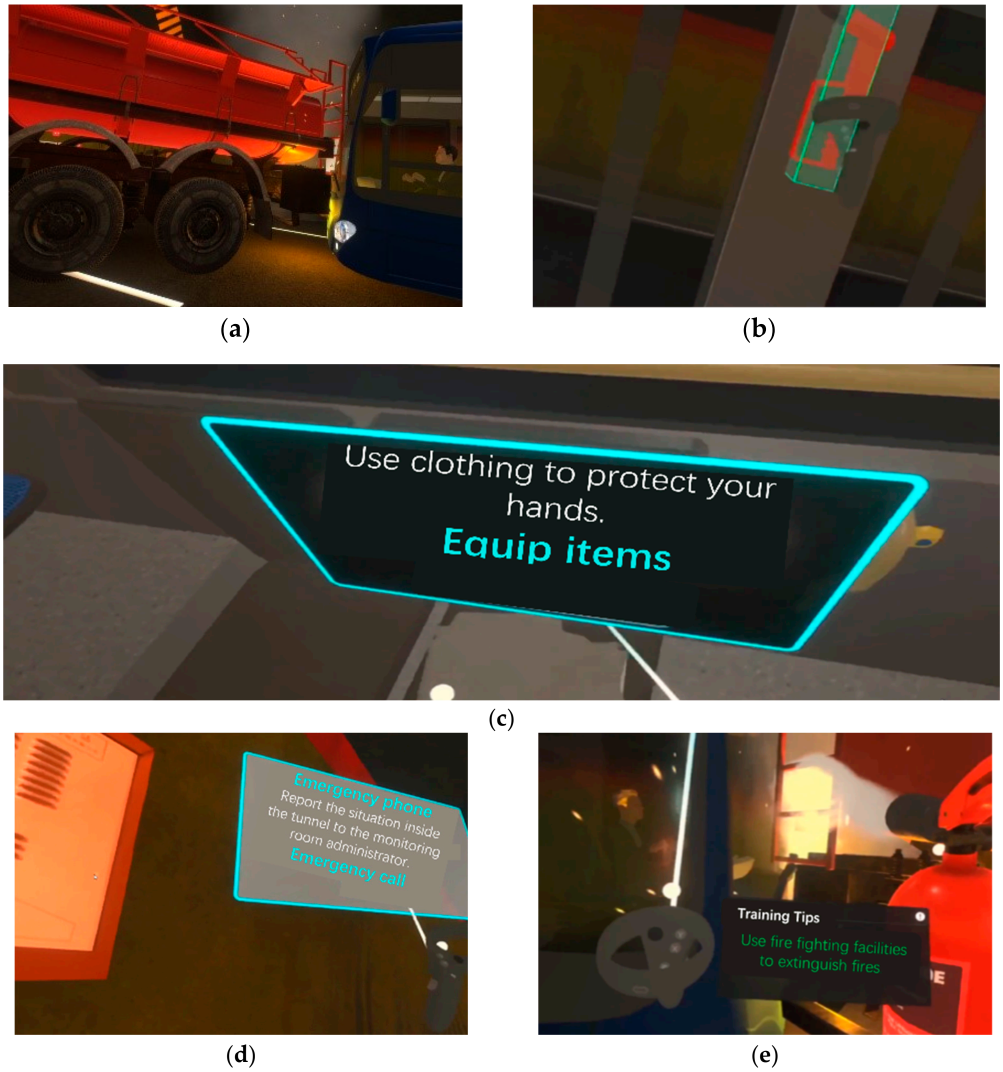


Figure 9. Training System 4: for the coach passengers. (**a**) A bus accident occurs; (**b**) Tip for the broken window hammer; (**c**) Instruction for the safe action; (**d**) Tip for locating and using the emergency phone; (**e**) Training tips for using firefighting facilities.

5. Evaluation

The platform was piloted in the Jinggangshan Tunnel of Jiangxi Expressway to complete the emergency response training and assessment. Jiangxi highway operations management conducts monthly simulation exercises with the operators of the central control room and emergency response group. A total of 32 staff have participated in the training and monthly assessment based on the system since October 2021. A comparative analysis of the changes in the training of the two departments for four months was carried out. Assessment results of the test paper and the average test time during five consecutive months are shown in Figure 10. The red "Scores" axis corresponds to the training assessment in the virtual environment, the paper test arranged by the highway management, and the total result. Specifically, the total result is the sum of the operation score and the test score. The blue axis corresponds to "Operation time", reflecting the efficiency of emergency response work. The left graph and right graph are similar in trend but different in specific values. According to the figure, the time has been decreased from 40 min to 17 min and from 67 min to 28 min for the control room and the emergency response group, respectively. Furthermore, the total scores consisting of both the operation and the test paper in the central control room and the emergency response group have increased from 84 to 173 and 99 to 176, respectively. The knowledge of emergency response in both sectors has been increased two-fold compared with that four months ago. Subjects can experience various emergency scenarios in a 3D virtual environment at any time, which has obvious advantages including efficiency, cost, and knowledge coverage. Furthermore, more knowledge and operational details are expected to be integrated into rescue training, according to the feedback from the participants.

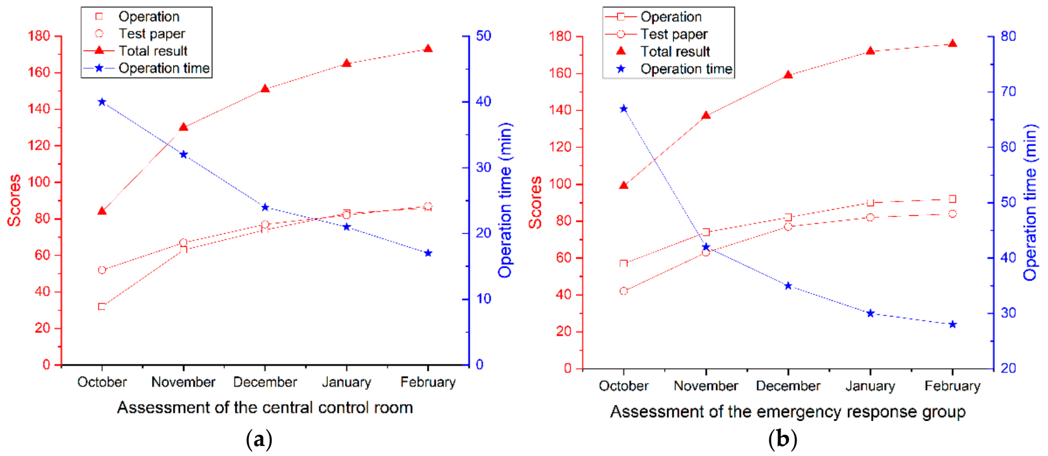


Figure 10. Assessment results of (**a**) the central room and (**b**) the emergency response group.

6. Discussion

In this paper, an emergency response platform in highway tunnels was developed based on BIM and VR technology. Three common emergency scenarios were conducted on the platform including illegal stops, car crashes, and heavy fire occurring in the tunnels. Four systems in the platform could satisfy the training requirement from the central control room, emergency response group, dangerous goods truck driver, and coach passengers. These systems exhibit the integration of BIM and VR on improving the information accessing and the training mode. The participants can deal more calmly with smoke and flames when responding to emergencies in reality through the immersive experience of VR. Furthermore, modes of real-time instructions and non-instructions make the participants learn the training more efficiently. The interaction between the front-line rescue team and the central control room is also improved in the training. The assessment results of the test paper and the average time in the training both indicate an evident improvement in the skill of emergency training. Therefore, this platform could be shared with similar highway tunnel agencies and explored with more comprehensive capabilities based on the proposed framework.

7. Conclusions

Each link of a highway tunnel from design and construction to logistics and operation needs collaborative work across several locations and domains. Safety and maintenance of a highway tunnel are regarded as one of the most complicated tasks in the highway system. Massive exchanges of information from different sources, as well as a large range of horrible accidents, are the main block. The timely and efficient information interaction presents a positive impact on engineering and maintenance schedules. This paper focuses on extending VR to the practical project through the "hand" of BIM. The proposed platform demonstrates successful integration of VR and BIM to access the information and improve the training.

First of all, this platform could identify the interdependence and the complexity of tasks in different training systems for several roles during the current practice. Second, the interdependencies between rescue tasks can be more explicit in the BIM + VR platform than in traditional training modes. The existing interdependency and complexity will be visualized for more efficient training in securing the safety of the highway. Given VR and BIM technology, the systems will provide an immersive viewpoint in simulating the real experience in highway tunnels. The viewpoint will be generated according to the location of participants staying, displaying the preset elements and procedures, and alleviating the mental workload of participants. With this in mind, the emergency response team of the highway system can see and visually learn the different scenarios of highway accidents. This paper facilitates the new era of employing advanced technologies in the management visualization of traditional industries. The proposed theoretical framework successfully integrates new technologies and exhibits good performance in practice. Much more practice on other visualized managements will be derived and built upon from the prototype in this paper. Future work will combine AR and more visualization technologies on developing the BIM + VR/VR platforms and expand the application scenarios. These scenarios will be initially identified by considering the cooperation between several sectors, the character of envisioned technologies, and the engagement from users. The conceptual model of scenarios will be discussed in future and completed by semi-structured interviews with practitioners in the industry. Information about the risk and health of the users will be attracted by the wireless sensing technologies in the updating BIM model.

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References

1. Li, Z.; Li, Y.; Ge, Y.; Wang, Y. Fire Simulation and Optimal Evacuation Based on BIM Technology. In Proceedings of the International Conference on Broadband Communications, Networks and Systems, Virtual Event, 28–29 October 2021; Springer: Cham, Switzerland, 2021.
2. Huang, S.; Huang, M.; Lyu, Y. Seismic performance analysis of a wind turbine with a monopile foundation affected by sea ice based on a simple numerical method. *Eng. Appl. Comput. Fluid Mech.* **2021**, *15*, 1113–1133. [CrossRef]
3. Ministry of Transport of the People's Republic of China. Statistical Bulletin on the Development of the Transportation Industry in 2020. *Financ. Account. Commun.* **2021**, *6*, 92–97.
4. Huang, H.; Huang, M.; Zhang, W.; Pospisil, S.; Wu, T. Experimental investigation on rehabilitation of corroded RC columns with BSP and HPFL under combined loadings. *J. Struct. Eng.* **2020**, *146*, 04020157. [CrossRef]
5. Guo, Y.; Yang, Y.; Kong, Z.; He, J. Development of Similar Materials for Liquid-Solid Coupling and Its Application in Water Outburst and Mud Outburst Model Test of Deep Tunnel. *Geofluids* **2022**, *2022*, 8784398. [CrossRef]
6. Sun, J.; Wang, J.; Zhu, Z.; He, R.; Peng, C.; Zhang, C.; Huang, J.; Wang, Y.; Wang, X. Mechanical Performance Prediction for Sustainable High-Strength Concrete Using Bio-Inspired Neural Network. *Buildings* **2022**, *12*, 65. [CrossRef]

7. Buttussi, F.; Chittaro, L. Effects of different types of virtual reality display on presence and learning in a safety training scenario. *IEEE Trans. Vis. Comput. Graph.* **2017**, *24*, 1063–1076. [CrossRef]
8. Gwynne, S.; Kuligowski, E.D.; Boyce, K.E.; Nilsson, D.; Robbins, A.; Lovreglio, R.; Thomas, J.; Roy-Poirier, A. Enhancing egress drills: Preparation and assessment of evacuee performance. *Fire Mater.* **2019**, *43*, 613–631. [CrossRef]
9. Getuli, V.; Capone, P.; Bruttini, A.; Isaac, S. BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach. *Autom. Constr.* **2020**, *114*, 103160. [CrossRef]
10. Kordestani, H.; Zhang, C.; Masri, S.F.; Shadabfar, M. An empirical time-domain trend line-based bridge signal decomposing algorithm using Savitzky–Golay filter. *Struct. Control. Health Monit.* **2021**, *28*, e2750. [CrossRef]
11. Sun, J.; Ma, Y.; Li, J.; Zhang, J.; Ren, Z.; Wang, X. Machine learning-aided design and prediction of cementitious composites containing graphite and slag powder. *J. Build. Eng.* **2021**, *43*, 102544. [CrossRef]
12. Shi, Y.; Du, J.; Lavy, S.; Zhao, D. A multiuser shared virtual environment for facility management. *Procedia Eng.* **2016**, *145*, 120–127. [CrossRef]
13. Carreira, P.; Castelo, T.; Gomes, C.C.; Ferreira, A.; Ribeiro, C.; Costa, A.A. Virtual reality as integration environments for facilities management: Application and users perception. *Eng. Constr. Archit. Manag.* **2018**, *25*, 90–112. [CrossRef]
14. Zhu, Z.; Wu, Y.; Han, J. A prediction method of coal burst based on analytic hierarchy process and fuzzy comprehensive evaluation. *Front. Earth Sci.* **2022**, *9*, 1424. [CrossRef]
15. Li, Z.; Chen, L.; Nie, L.; Yang, S.X. A novel learning model of driver fatigue features representation for steering wheel angle. *IEEE Trans. Veh. Technol.* **2021**, *71*, 269–281. [CrossRef]
16. Azhar, S. Role of visualization technologies in safety planning and management at construction jobsites. *Procedia Eng.* **2017**, *171*, 215–226. [CrossRef]
17. Froehlich, M.A.; Azhar, S. Investigating virtual reality headset applications in construction. In Proceedings of the 52nd Associated Schools of Construction Annual International Conference, Provo, UT, USA, 13–16 April 2016.
18. Feng, Z.; VGonzález, A.; Amor, R.; Lovreglio, R.; Cabrera-Guerrero, G. Immersive virtual reality serious games for evacuation training and research: A systematic literature review. *Comput. Educ.* **2018**, *127*, 252–266. [CrossRef]
19. Porzycki, J.; Schmidt-Polończyk, N.; Wąs, J. Pedestrian behavior during evacuation from road tunnel in smoke condition—Empirical results. *PLoS ONE* **2018**, *13*, e0201732. [CrossRef]
20. Cao, S.; Liu, X.; Chraibi, M.; Zhang, P.; Song, W. Characteristics of pedestrian's evacuation in a room under invisible conditions. *Int. J. Disaster Risk Reduct.* **2019**, *41*, 101295. [CrossRef]
21. Sidani, A.; Dinis, F.M.; Sanhudo, L.; Duarte, J.; Baptista, J.S.; Martins, J.P.; Soeiro, A. Recent tools and techniques of BIM-based virtual reality: A systematic review. *Arch. Comput. Methods Eng.* **2021**, *28*, 449–462. [CrossRef]
22. Mallam, S.C.; Nazir, S. Effectiveness of VR head mounted displays in professional training: A systematic review. *Technol. Knowl. Learn.* **2021**, *26*, 999–1041.
23. Shi, L.; Xiao, X.; Wang, X.; Liang, H.; Wang, D. Mesostructural characteristics and evaluation of asphalt mixture contact chain complex networks. *Constr. Build. Mater.* **2022**, *340*, 127753. [CrossRef]
24. Sun, J.; Tang, Y.; Wang, J.; Wang, X.; Wang, J.; Yu, Z.; Cheng, Q.; Wang, Y. A Multi-objective Optimisation Approach for Activity Excitation of Waste Glass Mortar. *J. Mater. Res. Technol.* **2022**, *17*, 2280–2304. [CrossRef]
25. Boton, C.; Rivest, L.; Ghnaya, O.; Chouchen, M. What is at the Root of Construction 4.0: A systematic review of the recent research effort. *Arch. Comput. Methods Eng.* **2021**, *28*, 2331–2350. [CrossRef]
26. Zhou, W.; Qin, H.; Qiu, J.; Fan, H.; Lai, J.; Wang, K.; Wang, L. Building information modelling review with potential applications in tunnel engineering of China. *R. Soc. Open Sci.* **2017**, *4*, 170174. [CrossRef] [PubMed]
27. Tse, T.-C.K.; Wong, K.-D.A.; Wong, K.-W.F. The utilisation of building information models in nD modelling: A study of data interfacing and adoption barriers. *J. Inf. Technol. Constr.* **2005**, *10*, 85–110.
28. Xu, L.; Liu, X.; Tong, D.; Liu, Z.; Yin, L.; Zheng, W. Forecasting Urban Land Use Change Based on Cellular Automata and the PLUS Model. *Land* **2022**, *11*, 652. [CrossRef]
29. Huang, S.; Liu, C. A computational framework for fluid–structure interaction with applications on stability evaluation of breakwater under combined tsunami–earthquake activity. *Comput.-Aided Civ. Infrastruct. Eng.* **2022**. [CrossRef]
30. Jung, Y.; Joo, M. Building information modelling (BIM) framework for practical implementation. *Autom. Constr.* **2011**, *20*, 126–133. [CrossRef]
31. Wang, S.; Guo, H.; Zhang, S.; Barton, D.; Brooks, P. Analysis and prediction of double-carriage train wheel wear based on SIMPACK and neural networks. *Adv. Mech. Eng.* **2022**, *14*, 16878132221078491. [CrossRef]
32. van Treeck, C.; Rank, E. Dimensional reduction of 3D building models using graph theory and its application in building energy simulation. *Eng. Comput.* **2007**, *23*, 109–122. [CrossRef]
33. Schlueter, A.; Thesseling, F. Building information model based energy/exergy performance assessment in early design stages. *Autom. Constr.* **2009**, *18*, 153–163. [CrossRef]
34. Cheng, M.-Y.; Chiu, K.-C.; Hsieh, Y.-M.; Yang, I.-T.; Chou, J.-S.; Wu, Y.-W. BIM integrated smart monitoring technique for building fire prevention and disaster relief. *Autom. Constr.* **2017**, *84*, 14–30. [CrossRef]
35. Liu, C.; Wu, D.; Li, Y.; Du, Y. Large-scale pavement roughness measurements with vehicle crowdsourced data using semi-supervised learning. *Transp. Res. Part C Emerg. Technol.* **2021**, *125*, 103048. [CrossRef]

36. Ban, Y.; Liu, M.; Wu, P.; Yang, B.; Liu, S.; Yin, L.; Zheng, W. Depth Estimation Method for Monocular Camera Defocus Images in Microscopic Scenes. *Electronics* **2022**, *11*, 2012. [CrossRef]
37. Han, Y.; Wang, B.; Guan, T.; Tian, D.; Yang, G.; Wei, W.; Tang, H.; Chuah, J.H. Research on Road Environmental Sense Method of Intelligent Vehicle Based on Tracking Check. *IEEE Trans. Intell. Transp. Syst.* **2022**, 1–15. [CrossRef]
38. Chen, H.; Hou, L.; Zhang, G.K.; Moon, S. Development of BIM, IoT and AR/VR technologies for fire safety and upskilling. *Autom. Constr.* **2021**, *125*, 103631. [CrossRef]
39. Sun, R.; Wang, J.; Cheng, Q.; Mao, Y.; Ochieng, W.Y. A new IMU-aided multiple GNSS fault detection and exclusion algorithm for integrated navigation in urban environments. *GPS Solut.* **2021**, *25*, 147. [CrossRef]
40. Meng, F.; Wang, D.; Yang, P.; Xie, G. Application of sum of squares method in nonlinear H∞ control for satellite attitude maneuvers. *Complexity* **2019**, *2019*, 5124108. [CrossRef]
41. Rüppel, U.; Schatz, K. Designing a BIM-based serious game for fire safety evacuation simulations. *Adv. Eng. Inform.* **2011**, *25*, 600–611. [CrossRef]
42. Luo, G.; Zhang, H.; Yuan, Q.; Li, J.; Wang, F.-Y. ESTNet: Embedded Spatial-Temporal Network for Modeling Traffic Flow Dynamics. *IEEE Trans. Intell. Transp. Syst.* **2022**, 1–12. [CrossRef]
43. Li, Y.; Che, P.; Liu, C.; Wu, D.; Du, Y. Cross-scene pavement distress detection by a novel transfer learning framework. *Comput.-Aided Civ. Infrastruct. Eng.* **2021**, *36*, 1398–1415. [CrossRef]
44. Sun, R.; Zhang, Z.; Cheng, Q.; Ochieng, W.Y. Pseudorange error prediction for adaptive tightly coupled GNSS/IMU navigation in urban areas. *GPS Solut.* **2022**, *26*, 28. [CrossRef]
45. Liu, J.; Chen, Y.; Wang, X. Factors driving waste sorting in construction projects in China. *J. Clean. Prod.* **2022**, *336*, 130397. [CrossRef]
46. Jiang, S.; Zhao, C.; Zhu, Y.; Wang, C.; Du, Y. A Practical and Economical Ultra-wideband Base Station Placement Approach for Indoor Autonomous Driving Systems. *J. Adv. Transp.* **2022**, *2022*, 3815306. [CrossRef]
47. Calandra, D.; Pratticò, F.G.; Migliorini, M.; Verda, V.; Lamberti, F. A Multi-role, Multi-user, Multi-technology Virtual Reality-based Road Tunnel Fire Simulator for Training Purposes. In Proceedings of the VISIGRAPP 2021: 16th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications, Vienna, Austria, 8–10 February 2021.
48. Mjelde, F.V.; Smith, K.; Lunde, P.; Espevik, R. Military teams–A demand for resilience. *Work* **2016**, *54*, 283–294. [CrossRef] [PubMed]
49. Liu, K.; Ke, F.; Huang, X.; Yu, R.; Lin, F.; Wu, Y.; Ng, D.W.K. DeepBAN: A temporal convolution-based communication framework for dynamic WBANs. *IEEE Trans. Commun.* **2021**, *69*, 6675–6690. [CrossRef]
50. Lin, Y.-H.; Liu, Y.-S.; Gao, G.; Han, X.-G.; Lai, C.-Y.; Gu, M. The IFC-based path planning for 3D indoor spaces. *Adv. Eng. Inform.* **2013**, *27*, 189–205. [CrossRef]
51. Yuan, H.; Yang, B. System Dynamics Approach for Evaluating the Interconnection Performance of Cross-Border Transport Infrastructure. *J. Manag. Eng.* **2022**, *38*, 04022008. [CrossRef]
52. Feng, W.; Wang, Y.; Sun, J.; Tang, Y.; Wu, D.; Jiang, Z.; Wang, J.; Wang, X. Prediction of thermo-mechanical properties of rubber-modified recycled aggregate concrete. *Constr. Build. Mater.* **2022**, *318*, 125970. [CrossRef]
53. Wang, B.; Li, H.; Rezgui, Y.; Bradley, A.; Ong, H.N. BIM based virtual environment for fire emergency evacuation. *Sci. World J.* **2014**, *2014*, 589016. [CrossRef]
54. Du, Y.; Qin, B.; Zhao, C.; Zhu, Y.; Cao, J.; Ji, Y. A novel spatio-temporal synchronization method of roadside asynchronous MMW radar-camera for sensor fusion. *IEEE Trans. Intell. Transp. Syst.* **2021**. [CrossRef]
55. Chen, P.; Pei, J.; Lu, W.; Li, M. A deep reinforcement learning based method for real-time path planning and dynamic obstacle avoidance. *Neurocomputing* **2022**, *497*, 64–75. [CrossRef]
56. Wang, J.; Meng, Q.; Zou, Y.; Qi, Q.; Tan, K.; Santamouris, M.; He, B.-J. Performance synergism of pervious pavement on stormwater management and urban heat island mitigation: A review of its benefits, key parameters, and co-benefits approach. *Water Res.* **2022**, *221*, 118755. [CrossRef] [PubMed]
57. Li, J.; Cheng, F.; Lin, G.; Wu, C. Improved Hybrid Method for the Generation of Ground Motions Compatible with the Multi-Damping Design Spectra. *J. Earthq. Eng.* **2022**, 1–27. [CrossRef]
58. Lu, S.; Ban, Y.; Zhang, X.; Yang, B.; Liu, S.; Yin, L.; Zheng, W. Adaptive control of time delay teleoperation system with uncertain dynamics. *Front. Neurorobotics* **2022**, 152. [CrossRef]