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A Review of Virtual Reality Fire Training Simulators Integrating CFD Data in Railway Transport

Mohammed Smouni [1], Ghizlane Aaboud [2], Taibi Saoudi [3], and Elmostapha Boudi [4]

[1] QSM Laboratory, Mohammadia School of Engineering, Mohammed V University, Rabat, Morocco
e-mail: smouniphd@gmail.com
[2] QSM Laboratory, Mohammadia School of Engineering, Mohammed V University, Rabat, Morocco
e-mail: aaboudghizlane@gmail.com
[3] QSM Laboratory, Mohammadia School of Engineering, Mohammed V University, Rabat, Morocco
e-mail: taibi@emi.ac.ma
[4] QSM Laboratory, Mohammadia School of Engineering, Mohammed V University, Rabat, Morocco
e-mail: boudi@emi.ac.ma

Abstract

Enhancing passenger safety in railway systems requires that train operators are effectively trained to manage diverse emergency scenarios, particularly during fire incidents. While full-scale drills have conventionally fulfilled this role, they are frequently constrained by exorbitant budgets and limited realism. Recent technology advances, particularly the integration of Computational Fluid Dynamics (CFD) with Virtual Reality (VR), present potential alternatives for immersive and economical training. This paper presents a review of the use of VR-based fire training simulators that integrate CFD data in railway firefighting and evacuation training. Using the CIIPP framework (Context, Input, Process, and Product), the performance of these simulators in railway is evaluated. Findings from the literature reveal that although VR and CFD have been individually applied in the railway sector with encouraging outcomes, their combined use remains underexplored. This gap highlights a significant opportunity for innovation in safety training.

Keywords: *computational fluid dynamics, fire, railway, training, virtual reality.*

1 Introduction

Rail transport is considered one of the safest modes of transport. Nevertheless, the risk of fire, although relatively rare in terms of occurrence, remains a critical safety issue due to the potentially serious consequences for passengers [1]. The unique characteristics of railway environments, including confined spaces, limited evacuation routes, and complex onboard infrastructure, make fire incidents particularly hazardous. In such scenarios, toxic

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smoke and heat can rapidly compromise visibility and air quality, significantly obstructing evacuation efforts and increasing the risk of injury or fatality [2-3].

Traditional fire safety training methods, including full-scale drills, have long played a role in preparing railway staff for emergencies. However, these approaches often fall short in replicating the dynamic and high-stress conditions of real-life fire events [4]. As a result, there is growing interest in more immersive and adaptable training solutions.

In recent years, VR has emerged as a transformative tool in fire safety training. By offering interactive, repeatable, and highly engaging scenarios, VR enables trainees to experience emergencies in a controlled yet realistic environment, thereby improving both knowledge retention and operational readiness [5]. Building on this innovation, researchers and developers have begun integrating CFD data into VR platforms, most notably using tools such as the Fire Dynamics Simulator (FDS). This integration enables the accurate simulation of fire behavior, smoke movement, and thermal conditions, thereby significantly enhancing the realism and educational value of training systems.

By embedding CFD-generated data into VR environments, trainees can engage with near-realistic fire scenarios that reflect the complex fluid dynamics of fire spread in railway contexts. This not only improves situational awareness but also supports the development of critical decision-making skills under pressure [6-7].

Despite its promise, the convergence of VR and CFD remains in an exploratory phase. Existing systems are often limited to proof-of-concept prototypes or narrowly scoped applications, lacking comprehensive interoperability, real-time responsiveness, and rigorous validation in operational railway contexts. While this technological convergence is still emerging, it has attracted increasing attention in the literature. This review synthesizes existing studies on VR and CFD applications in railway fire safety, with emphasis on their pedagogical relevance, implementation contexts, and evaluation strategies.
To structure this analysis, the study adopts the CIPP evaluation model—Context, Input, Process, Product—originally developed by Stufflebeam and Shinkfield [8]. This framework adds methodological rigor by providing a comprehensive lens for assessing educational technologies. The contribution of this paper consists in systematically reviewing VR- and CFD-based approaches and highlighting the lack of full integration between these technologies in operational railway fire training. By identifying conceptual and methodological gaps, the study aims to inform future research and support the development of more robust, validated, and institutionally deployable training solutions.

This paper is organized as follows: Section 1 introduces the topic and delineates the scope of the research. Section 2 explains the methodology adopted for selecting and analyzing the relevant literature. Section 3 presents the main findings of the review. Section 4 provides a discussion of these findings, examining their implications, limitations, and relevance within the broader research context. Finally, Section 5 concludes the paper by summarizing the key insights and proposing directions for future research.

2 Methodology

The literature review in this paper is organized into four main processes [9]: Acquisition of material, descriptive analysis, category selection, and material evaluation.

<u>Material acquisition</u> published between 2015 and 2025 was retrieved using the following structured approach:

- Defining period: all references available in the selected databases published up until July 2025 have been considered.
- A comprehensive search was performed across multiple reputable academic databases, including: Scopus, Web of Science, ScienceDirect
- The primary keywords and search terms used, individually and in various combinations, included:
    - "Virtual Reality" OR "VR training" OR "immersive training"
    - "Computational Fluid Dynamics" OR "CFD simulation" OR "fire dynamics"
    - "Railway safety" OR "train safety" OR "rolling stock fire" OR "rail transport"
    - "Emergency training" OR "firefighting training" OR "evacuation training"
    - "Simulator" OR "simulation"

Boolean operators were applied to combine railway-specific terms with VR and CFD, ensuring relevance and precision in the search results.

- Inclusion and Exclusion Criteria: The following criteria guided the selection of literature:
    - Inclusion Criteria:
        - Peer-reviewed journal articles, conference papers, and book chapters.
        - Research focusing on VR applications for training purposes, specifically within emergency response or safety contexts.
        - Studies published in English.
        - Studies on CFD applications for fire modeling, particularly in railway or analogous enclosed transportation environments (e.g., tunnels, train carriages, stations).
        - Literature discussing the integration or potential integration of VR and CFD for training or safety analysis, with a clear link to railway scenarios.
    - Exclusion Criteria:
        - Non-peer-reviewed sources
        - Studies solely on general VR applications without a training or safety focus.
        - Studies solely on CFD without an application to fire or training.

- Duplicate publications.
- Publications deemed not directly relevant to the specific intersection of railway, fire, VR, and CFD.

Descriptive analysis showed that 49 journal and conference papers in total were found. The modest number of publications reflects both the sector's cautious adoption of new technologies and the emerging nature of this research domain. 57% of the papers appeared in conference proceedings, suggesting rapid dissemination of preliminary findings. The remaining publications appeared in journals, signifying more mature research contributions. Engineering (64%) and Computer Science (21%) dominated the subject areas, confirming the interdisciplinary nature of this topic. This unique distribution suggests a fertile ground for further investigation and offers opportunities to integrate complementary expertise.

Selection of categories: Publications were systematically classified by thematic focus and core attributes. This process revealed that the papers primarily fall into three distinct categories: (1) VR and Advanced Simulation for Training & Evacuation, (2) CFD and Fire Dynamics Modeling, and (3) Evacuation Dynamics, Human Behavior, and General Railway Fire Safety. The literature clusters into three main areas: VR-based training, CFD and fire modeling, and evacuation dynamics in railway safety.

Evaluation of material: The final stage of the selection process involved a thorough validation of the chosen materials. Abstracts and conclusions were reviewed to ensure alignment with the review's objectives. This step ensured thematic coherence and preserved the focus of the analysis.

3 Results

This literature review is structured around three core themes, which are explored in the following sections:

3.1 VR and advanced simulation for training & evacuation in railways

This section examines how VR and simulation technologies are applied to railway training and evacuation. Several papers in this area highlight the use of VR for simulating evacuation procedures. Arias et al.[10] conducted VR evacuation experiments to evaluate way-finding systems, demonstrating VR's utility in assessing human response in controlled, simulated environments. Similarly, Aaboud et al. [11] specifically focused on using VR for fire evacuation training from passenger trains, underscoring its potential for specialized emergency preparedness. VR is also used for system validation, as in de Gordoa et al. [12], who tested automated train systems in a 3D virtual railway. D'Amico et al. [13] introduced TrainSim, a framework that generates LiDAR and camera data for realistic railway simulations. More integrated approaches are emerging, such as the work by Hu et al. [14] on an integrated VR-training simulation sand table for rail systems, and Jing et al. [15], who leveraged BIM and VR technology for fire evacuation simulation systems in rail transit stations. Wang et al. [7] developed a VR evacuation system that incorporates staff behavior in underground stations. Aaboud et al. [16] developed a VR-based serious games (SGs) prototype, specifically designed for fire safety training in passenger trains. These studies collectively illustrate the growing sophistication and potential of VR and advanced simulation as powerful tools for enhancing safety training and validating procedures in railway environments.

3.2 CFD & fire dynamics modeling in railways

This section reviews CFD applications in railway fire modeling, focusing on infrastructure safety and VR training accuracy. Enbaya et al [17], for instance, conducted a fire safety analysis of a railway compartment using CFD, providing insights into fire behavior within rolling stock. The complexities of ventilation systems in fire scenarios are a recurring theme, with Faggioni et al. [18] examining fire ventilation in metro stations with platform screen doors, and Teodosiu et al. [19] numerically evaluating ventilation efficiency in underground metro systems. Hua et al. [20] emphasized the importance of realistic fire scenarios in tunnel modeling. Efforts to manage smoke and its impact are vital, as noted by Lázaro et al.[21] exploring innovations for smoke management in passenger trains. Beyond general fire dynamics, studies also investigate specific consequences of fire. For example, Nuianzin et al. [22] analyzed temperature regimes in cable tunnels, and Přibyl et al. [23] modeled the impacts of fires on critical road infrastructure, including tunnels. The effectiveness of fire suppression systems is also assessed computationally, as demonstrated by Ong et al. [24], who evaluated high-pressure water mist systems for railcars. Full-scale tests by Sturm et al. [25] and Thaller et al. [26] help validate CFD models and improve training reliability. Complementarily, Chochev & Arabadzhieva [27] conducted compartment-level CFD simulations in railway passenger cars, providing detailed insights into heat release dynamics and smoke propagation under confined conditions. Finally, Smouni et al.[1] directly addressed fire modeling in passenger rolling stock evacuation, underscoring the direct link between accurate fire simulation and evacuation analysis.

3.3 Evacuation dynamics, human behavior & general railway fire safety

This section broadens the scope to encompass critical areas, including evacuation dynamics, human behavior during emergencies, and overarching fire safety measures within the railway transportation sector.

Many studies simulate passenger evacuation in railway environments. Chen H. et al. [28] and Chen Y. et al. [29] provide examples of numerical and emergency evacuation simulations in large railway hubs and subway stations, respectively, highlighting the complexities of managing large crowds. Further studies delve into various aspects of evacuation simulation in metro-rail transit, including emergency evacuation in fire degradation mode (Jiaojiao & Jin, [30]), light rail stations based on BIM technology (Diao & Guo, [31]), and urban rail transit stations (Lin et al.[32]). Jahedinia et al. [33] studied passengers with luggage, while Lu et al. [34] examined fire evacuation behavior. Research also examines specific evacuation challenges, such as evacuation from high-speed trains (Li L. et al. [35]), metro trains during fire incidents (Song et al. [36]), and fire trains in railway tunnels (Yu et al. [37]). Fridolf et al. [38] analyzed human movement in smoke-filled underground systems, highlighting key challenges. Studies also analyze evacuation from elevated platforms in railway tunnels (Carlson et al. [39]) and evacuation safety in Mass Rapid Transit systems under fire scenarios (Chang et al. [40]). Methodological advancements in general evacuation simulation are also evident, with studies on emergency evacuation in metro-rail transit stations (Gulanur et al. [41]), numerical simulation of evacuation in subway stations (Li Z.-Y. et al. [42]), and evacuation strategies for air-rail intermodal hub stations (Si et al. [43]). Furthermore, Liu B. et al. [44] and Liu Y. et al. [45] contribute to understanding fire impact and evacuation in integrated rail-road tunnels and light rail vehicles, respectively. Reviews like those by Aaboud et al. [4] further consolidate existing methods for estimating passenger train evacuation times.

Beyond evacuation, this group also covers broader aspects of railway fire safety and infrastructure design. This includes the development of emergency tunnel ventilation strategies by de Los Rios et al. [46], unidirectional ventilation for steep metro rail tunnels (Biotto et al. [47]), and the coupling of ventilation and egress analyses by Louie and Li [48] to design safer stations. Structural considerations for fire safety are addressed by Bakhshi et al. [49] regarding precast segments for tunnels and by Harris et al. [50] concerning compartmentation for train passenger fire safety. The determination of cross-passage spacing from fractional practical dose analysis also contributes to tunnel safety design (Marsico et al. [51]). General preparedness and safety practices are examined by Tajedi et al.[52], comparing fire safety preparedness across train operators, while Restel et al. [53] focused on identifying safety-relevant activities of train crews. Studies also examine detailed fire safety design for subways, including arson-initiated fires (Bassi et al. [54]) and the safety aspects of electrified lines entering tunnels with fire (Pawlik [55]). Taken as a whole, the literature reveals both the complexity of railway fire safety and the growing potential of integrated VR-CFD solutions for training.

4 Discussion

This section presents a comprehensive analysis of the current research, utilizing the CIPP framework, as illustrated in Fig. 1.

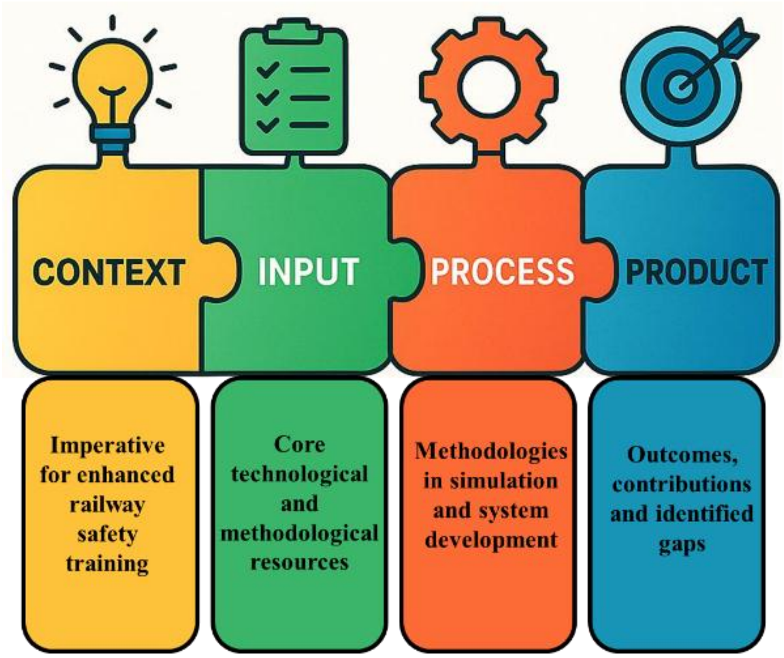

Fig. 1: CIPP framework

A detailed CIPP analysis for each reviewed paper is presented in Tab. 1.

Table 1: CIPP Analysis of Selected VR & CFD Papers in Railway

Ref.	Context	Input	Process	Product
[1]	Understand and improve the evacuation of passenger rolling stock in the event of a fire.	Fire modeling software, parameters related to car design, and passenger behavior.	Simulate fire scenarios and passenger evacuation.	Data on evacuation times, bottlenecks, and potential improvements.
[4]	Ensure rapid and effective evacuation in railway emergencies.	Review of various methods for evacuation time estimation.	Analyzing and synthesizing existing methods.	Improved understanding and estimation accuracy of railway evacuation times.
[7]	Enhance fire evacuation in metro stations by utilizing VR, taking into account staff behavior and response patterns.	VR technology, simulation software, and data on staff and passenger behavior.	Develop and test a VR-based fire evacuation simulation.	Evaluation of the effectiveness of the VR system and insights into the role of staff in evacuation.

Ref.	Context	Input	Process	Product
[10]	Challenges of evacuation in complex, large-scale facilities, leveraging virtual environments.	VR platform for evacuation experiments and way-finding system designs.	Conducting VR-based evacuation experiments and data collection.	Insights into the effectiveness of way-finding systems and evacuation behavior in virtual settings.
[11]	Need for realistic and safe training for fire evacuation from passenger trains, leveraging immersive technologies.	VR technology, passenger train models, fire scenarios, and evacuation procedures.	Development and application of a VR system for fire evacuation training in passenger trains.	A VR-based training tool for passenger train fire evacuation, enhancing preparedness and decision-making.
[12]	Demand for rigorous validation of automated train systems in various operational scenarios.	3D Virtual Railway Environment; Scenario-based validation methodology.	Utilizing a virtual environment to perform validation tests for automated train systems.	Validated and more reliable automated train systems through virtual testing, reducing real-world risks.
[13]	Need for realistic simulation environments and synthetic data for railway system development and testing.	TrainSim framework; LiDAR and camera data generation capabilities.	Developing and utilizing the simulation framework for data synthesis.	High-quality synthetic datasets to train and validate railway systems, enhancing realism in virtual testing.
[14]	Need for a comprehensive and immersive training tool for various aspects of rail system operations and emergencies.	VR technology, rail system models, simulation principles, and training objectives.	Design, development, and integration of a VR training simulation sand table for rail systems.	A novel integrated VR simulation system for multi-aspect rail system training and operational understanding.
[15]	Developing advanced tools for fire evacuation training and planning in rail transit stations.	Building Information Modeling data, VR technology, fire evacuation principles, and station design.	Design and integration of BIM and VR for a comprehensive fire evacuation simulation system.	A comprehensive fire evacuation simulation system leveraging both BIM and VR for enhanced training and planning in rail transit stations.

Ref.	Context	Input	Process	Product
[16]	Besoin croissant de solutions immersives pour la formation incendie dans les trains de passagers, face aux limites des méthodes traditionnelles	Modèles VR immersifs, scénarios d'évacuation ferroviaire, retours utilisateurs.	Conception d'un simulateur VR ; évaluation ergonomique et pédagogique auprès d'utilisateurs en environnement simulé.	Prototype fonctionnel de simulateur VR; amélioration de la préparation opérationnelle et de la compréhension des comportements en situation d'urgence.
[17]	Assessing and enhancing fire safety within enclosed railway compartments.	CFD software, railway compartment design, and fire parameters.	Application of CFD for detailed fire safety analysis within a railway compartment.	Detailed understanding of fire behavior and thermal conditions within a railway compartment, informing safety measures.
[18]	Fire safety challenges in modern metro stations, which feature specific architectural elements such as platform screen doors.	Design principles for fire ventilation systems, station layout, and potentially CFD/simulation data.	Design, analysis, and optimization of ventilation systems for these specific conditions.	Improved fire ventilation strategies tailored for metro stations with platform screen doors.
[19]	Optimize ventilation systems in underground metro rail transport systems.	Numerical modeling techniques, data on ventilation system design, and performance.	Simulate ventilation performance under various conditions.	Recommendations for Enhancing Ventilation Efficiency and Air Quality.
[20]	Establishing realistic and standardized fire scenarios for fire safety design and assessment in railway tunnels.	Historical fire data, railway tunnel characteristics, and fire modeling principles.	Development of methodologies for defining appropriate design fire scenarios for railway tunnels.	A set of well-defined design fire scenarios for use in railway tunnel fire safety engineering and assessment.

Ref.	Context	Input	Process	Product
[21]	Critical need for effective smoke control to ensure passenger safety during fires in trains.	Innovative smoke management technologies and design principles for passenger trains.	Development, testing, or analysis of new smoke management systems.	Enhanced smoke control within passenger trains improves safety and survivability.
[22]	Understanding fire behavior and temperature distribution in specialized environments, such as cable tunnels.	Experimental data, fire parameters (e.g., fuel load, ventilation), and thermal modeling techniques.	Conducting investigations to establish relationships between fire parameters and temperature regimes in cable tunnels.	Regularities and predictive models for temperature profiles during fires in cable tunnels, informing fire suppression strategies.
[23]	Assessing fire impacts on critical road infrastructure (tunnels) to improve safety and resilience.	Computer modeling software, tunnel structural data, and fire load characteristics.	Application of computer modeling to simulate and predict fire consequences in road tunnels.	Detailed understanding of the fire impact on road tunnels, informing design, emergency response, and recovery strategies.
[24]	Enhancing fire suppression and passenger survivability within rail cars using advanced systems.	Computational analysis tools (e.g., CFD), data on high-pressure water mist systems, and rail car designs.	Computational analysis to evaluate the effectiveness of on-board water mist systems.	Assessment of high-pressure water mist systems, demonstrating their performance in improving survivability in rail car fires.
[25]	Investigate smoke propagation in long rail tunnels.	Hot smoke testing equipment, sensors, and tunnel infrastructure.	Conduct large-scale hot smoke tests in tunnels.	Data on smoke propagation patterns and factors influencing smoke movement.
[26]	Understand smoke propagation in cross-passages of long rail tunnels.	Large-scale testing equipment, sensors, and tunnel infrastructure.	Conduct large-scale tests to measure smoke movement in cross-passages.	Data on smoke propagation patterns and the effectiveness of cross-passages.

Ref.	Context	Input	Process	Product
[27]	Risques d'incendie dans les compartiments ferroviaires fermés, avec propagation rapide de chaleur et de fumée ; nécessité de modélisation prédictive pour améliorer la conception et la sécurité.	Géométrie réaliste d'un compartiment ferroviaire ; logiciel FDS ; grille de calcul fine ; matériaux combustibles simulés.	Simulation CFD via FDS ; calcul dynamique du champ de température et du taux de libération de chaleur (HRR) ; validation par comparaison avec des données expérimentales.	Modèle validé pour prédire les scénarios d'incendie; confirmation de l'utilité de FDS pour la conception sécuritaire des compartiments.
[28]	Safety concerns related to passenger evacuation and thermal hazards in large railway station hubs during emergencies.	Numerical simulation techniques (e.g., CFD for heat fluxes, agent-based models for evacuation).	Conducting detailed numerical simulations to model fire and evacuation dynamics.	Quantitative data on evacuation patterns and heat exposure, informing safety design and emergency planning.
[29]	Specific emergency evacuation challenges at a critical transit infrastructure point (subway station and bridge connection).	Evacuation simulation models: A Case study approach for real-world application.	Applying simulation tools to a specific geographical context.	Site-specific insights and recommendations for improving emergency evacuation procedures.
[30]	Addressing emergency evacuation challenges in metro stations under degraded conditions (e.g., partial system failure, reduced visibility due to fire).	Evacuation simulation models, parameters describing fire degradation modes, and metro station layouts.	Conducting simulation studies to assess evacuation performance and identify risks under fire degradation.	Insights into evacuation dynamics and potential bottlenecks in metro stations during fire degradation modes.

Ref.	Context	Input	Process	Product
[31]	Improving the efficiency and accuracy of emergency evacuation planning in light rail stations using advanced technologies.	Building Information Modeling technology, station layouts, and evacuation principles.	Development of an Evacuation Model Leveraging BIM for Light Rail Stations.	A BIM-based model for simulating and optimizing fire emergency evacuations in light rail stations.
[32]	Improving emergency response and evacuation planning for urban rail transit stations.	Simulation software, station architectural data, and emergency scenarios.	Performing simulations to model and assess emergency evacuation scenarios in urban rail transit stations.	Optimized emergency evacuation plans and design recommendations for urban rail transit stations.
[33]	Understanding complex pedestrian behavior, particularly the impact of luggage, during evacuation in specific metro environments.	Floor field Cellular Automata model, empirical data on luggage impact, and the layout of the Tehran metro-rail corridor.	Application and customization of a CA model for simulating the evacuation of passengers carrying luggage.	Improved understanding and predictive capabilities for evacuation behavior in specific metro corridors, especially concerning luggage.
[34]	Optimizing metro station design and emergency response by understanding fire emergency evacuation behavior.	Human behavior models, metro station layouts, and simulation techniques.	Studying evacuation behavior through simulation to inform safety-conscious design.	Design principles and practical recommendations for enhancing the safety of metro station evacuations based on behavioral insights.
[35]	Demand for specialized and robust methodologies for analyzing evacuation from high-speed trains.	HSTEAM methodology, high-speed train characteristics, and evacuation data.	Application and refinement of the HSTEAM methodology for evacuation analysis.	A comprehensive methodology for analyzing high-speed train evacuation provides a systematic assessment.

Ref.	Context	Input	Process	Product
[36]	Enhance evacuation procedures in the event of a fire in the subway.	Numerical modeling techniques, data on car layout, and passenger behavior.	Simulate evacuation scenarios with different fire conditions.	Insights into factors affecting evacuation efficiency and potential areas for improvement.
[37]	Study the evacuation of passengers from a burning train in a rail tunnel.	Simulation software, data on car layout, passenger behavior, and tunnel characteristics.	Simulate evacuation scenarios under different fire conditions.	Data on evacuation times, bottlenecks, and factors affecting evacuation efficiency.
[38]	Understanding and accurately modeling human behavior during evacuation in low-visibility, smoke-filled underground environments.	Evacuation models, smoke propagation data, and human movement characteristics.	Developing and refining methods for representing evacuation movement under challenging smoke conditions.	More accurate and realistic models for simulating evacuation in smoke-filled underground transportation systems.
[39]	Specific evacuation challenges posed by elevated platforms in railway tunnels.	Real-world or simulated evacuation tests.	Planning, conducting, and analyzing evacuation experiments.	Data and insights to inform and improve evacuation procedures for railway tunnels.
[40]	Evacuation safety concerns during fire scenarios within the unique architecture of elevated MRT systems.	Fire scenarios: Analytical methods for evacuation safety assessment.	Performing safety analysis through simulations or calculations.	Evaluation of evacuation safety and identification of risks for specific MRT structures.
[41]	Optimizing emergency evacuation procedures and safety in metro-rail transit stations.	Station layout data, pedestrian movement models, and various emergency scenarios.	Conducting detailed simulations of emergency evacuation within a metro-rail transit station.	Insights and recommendations for improving evacuation efficiency and safety in metro-rail transit stations.

Ref.	Context	Input	Process	Product
[42]	Addressing the complexities of passenger evacuation in subway stations, especially during emergencies.	Numerical simulation tools, subway station layouts, and pedestrian behavior models.	Conducting detailed numerical simulations to model and analyze evacuation dynamics in a subway station.	Insights into evacuation efficiency and bottlenecks in subway stations through numerical simulation.
[43]	Improve evacuation strategies in air-rail intermodal stations.	Simulation software, parameters related to station layout, and passenger behavior.	Run simulations of different evacuation strategies.	Optimized evacuation strategies and recommendations for station design.
[44]	Unique challenges of fire and evacuation in complex rail-and-road integrated tunnels, such as the Yangtze River-Crossing Tunnel.	Fire dynamics models, personnel evacuation models, and specific tunnel design parameters.	Simulation and analysis of fire impact and evacuation under complex tunnel conditions.	Understanding of fire propagation and human evacuation behavior in integrated tunnels, informing safety measures.
[45]	Assessing and enhancing fire safety and evacuation procedures specifically for light rail vehicles.	Light rail vehicle design, fire scenarios, and evacuation analysis methods.	Conducting comprehensive fire and evacuation analysis tailored to light rail vehicles.	Detailed analysis of fire behavior and evacuation patterns in light rail vehicles, leading to safety improvements.
[46]	Need for effective smoke management and emergency response in railway tunnels, specifically for the WMATA system.	Data on tunnel characteristics, fire scenarios, and ventilation system designs of WMATA.	Development and testing of a specific ventilation strategy for WMATA.	A refined emergency tunnel ventilation strategy for the WMATA railway system.
[47]	Challenges of smoke and heat control in steep metro rail tunnels during fire incidents.	Unidirectional ventilation systems as a smoke management solution.	Design, modeling, or analysis of ventilation strategies.	Improved smoke control, visibility, and safety conditions within tunnels.

Ref.	Context	Input	Process	Product
[48]	Need for integrated approaches to ventilation and egress design to optimize safety in station environments.	Ventilation modeling tools, egress simulation software, and station design parameters.	Methodologies for Combining Ventilation and Egress Analyses for a Holistic Safety Design.	Safer station designs through integrated consideration of ventilation and evacuation dynamics.
[49]	Fire safety requirements for structural components in light-rail tunnels.	Design Principles and Material Properties for Fire Resistance.	Application of design methodologies and fire engineering principles.	Enhanced fire resistance and structural integrity of light-rail tunnels during fire events.
[50]	Enhancing fire safety within train carriages through effective compartmentation strategies.	Principles of compartmentation, fire-resistant materials, and relevant design standards for trains.	Analysis and development of compartmentation techniques specifically for train passenger safety.	Improved design principles for train passenger carriages to enhance fire containment and safety.
[51]	Optimizing the placement of cross-passages in tunnels to facilitate safe evacuation and minimize exposure to harmful substances.	Fractional Effective Dose analysis, tunnel fire scenarios, and human exposure data.	Application of FED analysis to determine optimal cross-passage spacing for safe evacuation.	Data-driven guidelines for cross-passage spacing in tunnels to maximize evacuation safety and reduce exposure risk.
[52]	Evaluate fire safety preparedness in metro stations in Malaysia.	Fire safety standards, operational procedures, and infrastructure.	Compare practices in Malaysia with those of developed countries.	Identification of areas for improvement in fire safety preparedness.
[53]	Identify safety-relevant activities of train crews.	Functional Resonance Analysis Method.	Analyze train crew activities in various scenarios.	List of safety-relevant activities and potential areas for improvement.
[54]	Specific threat of arson-initiated fires and the need for robust fire safety in subways.	Innovative fire safety design strategies; Coordination mechanisms.	Implementation processes for detailed fire safety designs.	Comprehensive fire safety plans for subways, resilient against arson threats.

Ref.	Context	Input	Process	Product
[55]	Specific fire safety challenges related to electrified railway lines entering tunnels, particularly in the context of Poland.	Data on electrified railway systems, tunnel characteristics, and fire safety regulations/procedures in Poland.	Analysis of safety aspects and potential risks associated with fires on electrified lines in tunnels.	Identification of key safety considerations and recommendations for managing fire risks on electrified railway lines in tunnels.

Table 1 presents the CIPP analysis per paper. The following synthesis identifies key trends and implications for the field.

<u>Context: Imperative for enhanced railway safety training</u>

The context of railway systems underscores the need for advanced safety measures and training, given the challenges posed by confined spaces, high passenger densities, and the rapid spread of smoke, heat, and toxic gases. Traditional training methodologies are limited due to costs, logistical complexities, and reduced realism. The growing recognition of human behavior as a critical factor in emergency outcomes underscores the need for accurate training.

<u>Input: Core technological and methodological resources</u>

The "Input" component reveals the research methods used in this field, including computational tools such as CFD and Agent-Based Modeling, as well as pedestrian dynamics simulators. VR technologies are also crucial for immersive training studies. Additional inputs include Building Information Modeling and 3D geometric data. Crucially, empirical data derived from full-scale fire tests and actual evacuation drills frequently serve as vital real-world inputs, indispensable for validating the fidelity and reliability of the developed computational models and virtual simulations. Furthermore, established fire safety codes, international standards (e.g., EN, NFPA), and specific railway regulations consistently guide the definition of realistic fire scenarios and emergency response criteria, acting as essential normative inputs.

<u>Process: Methodologies in simulation and system development</u>

The "Process" dimension of research describes the methods applied in the studies. The most common process involves numerical simulation, where researchers analyze intricate scenarios using CFD, ABM, or integrated modeling approaches. This includes defining fire sources, configuring ventilation conditions, and characterizing human behavior. A significant portion of the research is dedicated to developing and validating new computational models for fire spread, smoke dispersion, evacuation dynamics, and human decision-making. Many papers detail a systematic process of scenario analysis, in which several hypothetical conditions are tested to assess the impact of various variables (e.g., fire size, emergency ventilation system failure, blocked exits) on safety outcomes. For VR studies involve designing environments with realistic graphics, interfaces, and physical models. Some studies include real-world tests (e.g., smoke drills) for model calibration. Few studies detail the dynamic integration of CFD into VR fire training simulators for railway use.

Product: Outcomes, contributions, and identified gaps

The "Product" aspect highlights the key findings of understanding of fire dynamics, smoke propagation, and complex human evacuation behaviors within diverse railway scenarios. This knowledge can lead to recommendations for infrastructure design, operational procedures, and emergency response protocols. Studies have produced validated models, simulation tools, and VR prototypes, which can be used for safety assessments and training initiatives. Specific outcomes often include the identification of strategies that can demonstrably reduce evacuation times or optimize the efficiency of emergency egress from railway facilities. For papers directly addressing VR applications, the product frequently includes evidence of improved training effectiveness, enhanced spatial awareness, or better decision-making capabilities for trainees in simulated emergency contexts.

Despite the methodological diversity and technological sophistication observed across the reviewed studies, several limitations persist. First, many VR-based training systems lack dynamic environmental feedback, often relying on static or pre-scripted scenarios that do not reflect real-time fire behavior. Conversely, CFD models—while highly accurate in simulating smoke and heat propagation—are rarely embedded within interactive training platforms, limiting their pedagogical reach. Furthermore, few studies address the ergonomic and cognitive load implications of immersive training, which are crucial for operational adoption. The absence of standardized validation protocols across VR–CFD systems also hinders cross-comparability and institutional integration. Future research should prioritize the co-development of interoperable VR–CFD frameworks, calibrated with empirical fire data and designed for modular adaptation to diverse rolling stock configurations. Additionally, longitudinal studies assessing trainee performance and retention in immersive fire scenarios would provide valuable insights into the long-term efficacy of such systems. Bridging these gaps will be essential to move beyond proof-of-concept prototypes toward scalable, institutionally validated training solutions.

5 Conclusions

This review has explored the emerging domain of VR-based fire safety training in railway contexts, with a particular focus on the integration of CFD data. Through a structured CIPP analysis, the study highlights the pressing need for realistic and effective training solutions ("Context"), the availability of advanced technological resources ("Input"), and the methodological advancements in simulation and system design ("Process"). However, the synthesis reveals a critical gap: the seamless, real-time incorporation of CFD-generated fire dynamics into immersive VR environments for operational railway training remains largely unexplored. Addressing this gap offers a promising avenue for innovation. Future research should aim to establish robust frameworks that enable dynamic interoperability between CFD engines and VR platforms, assess the impact of high-fidelity simulations on user performance under stress, and develop standardized protocols for validating these integrated systems in institutional settings.

Conflicts of Interest

The authors declare no conflict of interest.

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References

[1] M. Smouni, G. Aaboud and E. Boudi, (2022). Fire Modeling of Passengers Rolling Stock Evacuation. *International Conference on Engineering Research and Application*, 2936: 030002.AIP.

[2] S. Huang, S. Lu, S. Lo, C. Li and Y. Guo, (2018). Experimental study on occupant evacuation in narrow seat aisle. *Physica A: Statistical Mechanics and its Applications*, 502, pp 506-517.

[3] M. Oswald, C. Lebeda, U. Schneider and H. Kirchberger, (2007). Full-Scale Evacuation Experiments in a smoke filled Rail Carriage — a detailed study of passenger behaviour under reduced visibility. *Pedestrian and Evacuation Dynamics 2005*, (pp. 41-55). Springer Berlin.

[4] G. Aaboud, M. Smouni, and E. Boudi. (2022). A Review of Methods Used for Estimating Passenger Train Evacuation Time. *2nd International Conference on Innovative Research in Applied Science, Engineering and Technology*, (pp. 1-7). IEEE.

[5] H. He, J. Chen, J. Zhu, Y. Yang and H. Zheng,(2024). Design and development of an integrated virtual-reality training simulation sand table for rail systems. *Information*, 15:3 , p. 141.

[6] M. Tzani, J. Besharat, V. Charalampous and C. Stylios, (2020). Building a Virtual Reality Fire Environment based on Fire Dynamic Simulator. *Proceedings of the 2020 IEEE International Conference on Information Technologies*. (pp 41-45). IEEE.

[7] Z. Wang, Z. Mao, Y. Li, L. Yu and L. Zou, (2023).VR-based fire evacuation in underground rail station considering staff's behaviors: model, system development, and experiment. *Virtual. Reality*, vol. 27, pp. 1145-1155.

[8] V. R. Matthew and H. Yamat, (2020). Evaluation of Highly Immersive Program (HIP) Using CIPP Model. *International Journal of Academic Research in Business and Social Sciences*. 10 :4 , pp. 509-526.

[9] M. Rickinson and H. May, (2009). A Comparative Study of Methodological Approaches to Reviewing Literature. *York UK: Higher Education Academy*, https://www.researchgate.net/profile/Mark-Rickinson/publication/265008044_A_Comparative_Study_of_Methodological_Approaches_to_Reviewing_Literature/links/56b31d6008aed7ba3fee2f8f/A-Comparative-Study-of-Methodological-Approaches-to-Reviewing-Literature.pdf (Accessed:July 2025).

[10] S. Arias, S. la Mendola, J. Wahlqvist, O. Rios, D. Nilsson and E. Ronchi, (2019). Virtual Reality Evacuation Experiments on Way-Finding Systems for the Future Circular Collider. *Fire Technology*, vol. 55, pp. 2319-2340.

[11] G. Aaboud, M. Smouni, S. Taibi, and E. Boudi. (2022). Virtual Reality for Fire Evacuation from Passenger Train. *Maejo International Journal of Science & Technology*, vol. 16, pp. 238-248.

[12] J. A. I. de Gordoa, S.García, L.P.V de la Iglesia, I. Urbieta, N. Aranjuelo and M. Nieto, (2023). Scenario-Based Validation of Automated Train Systems Using a 3D Virtual Railway Environment. *IEEE 26th International Conference on Intelligent Transportation Systems (ITSC),* Bilbao, Spain, (pp. 5072-5077). IEEE.

[13] G. D'Amico, M. Marinoni, F. Nesti, G. Rossolini, G. Buttazzo and S. Sabina, (2023). TrainSim: A Railway Simulation Framework for LiDAR and Camera Dataset Generation. *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, pp. 15006-15017.

[14] H. Hu, J. Chen, J. Zhu, Y. Yang and H. Zheng, (2024). Design and Development of an Integrated Virtual-Reality Training Simulation Sand Table for Rail System. *Information Switzerland*, 15: 3.

[15] G. Jing, X. Yingqi, W. Hongtao, W. Jianyu, X. Sibo and L. Mingyu, (2023). Design of Fire Evacuation Simulation System for Rail Transit Station Based on BIM and VR Technology. *Proceedings of the 2023 International Conference on Culture Oriented Science and Technology CoST*, (pp. 174-177). IEEE.

[16] G. Aaboud, M. Smouni, S. Taibi, and E. Boudi. (2025). Virtual Reality Simulations for Effective Fire Safety Training in Passenger Trains. *International Journal of Advances in Soft Computing and its Application*, vol. 17, pp. 67-82.

[17] A. Enbaya, A. Asim, R. Mishra and B. K. N. Raj Rao, (2015). Fire safety analysis of a railway compartment using Computational Fluid Dynamics. *International Journal of COMADEM*, vol. 18, pp. 37-44.

[18] N. Faggioni, S. Franzoni and F. Devia, (2019). Fire ventilation systems in a metro station equipped platform screen doors. *Proceedings of the WTC 2019 ITA-AITES World Tunnel Congress*, (pp. 4778-4787). TAYLOR & FRANCIS

[19] C. Teodosiu, V. Ilie, R. Dumitru and R. Teodosiu, (2016). Numerical Evaluation of Ventilation Efficiency in Underground Metro Rail Transport Systems. *Energy Procedia*, vol. 85, pp. 539-549.

[20] N. Hua, A. F. Tessari and N. Elhami-Korasani, (2019). Design fire scenarios for railway tunnel fires. *20th Congress of IABSE*, the Evolving Metropolis Report,(pp. 82-86). IABSE.

[21] M. Lázaro, D. Lázaro, E. Cortabarria and D. Alvear, (2020). Innovations for smoke management in passenger trains. *Journal of Fire Sciences*, vol. 38, pp. 194-211.

[22] O. Nuianzin, M. Kryshtal, A. Nesterenko, D. Kryshtal and T. Samchenko, (2018).Investigation of the regularities of temperature regime of fire in cable tunnels depending on its parameters. *7th International Scientific Conference "Reliability and Durability of Railway Transport Engineering Structures and Buildings*", 230:02022. MATEC Web of Conferences.

[23] P. Přibyl, O. Přibyl and J. M. Czech, (2018). Computer modelling of fire consequences on road critical infrastructure – tunnels. *Structural Monitoring and Maintenance*, vol. 5, pp. 363-377.

[24] I. Ong, T. Eng and G. Kildare, (2015). Computational analysis to assess the performance of on-board high pressure water mist systems for rail cars for improving survivability. *Proceedings of the BHR Group 16th International Symposium on Aerodynamics Ventilation and Fire in Tunnels*, (pp. 343-357).

[25] P. Sturm, J. Rodler, T. Thaller, D. Fruhwirt and P. Fößleitner, (2019). Hot smoke tests for smoke propagation investigations in long rail tunnels. *Fire Safety Journal*, vol. 105, pp. 196-203.

[26] T. Thaller, P. Sturm and J. Rodler, (2017). Smoke propagation in the region of cross-passages in long railway tunnels - Results from full scale tests. *Geomechanik Und Tunnelbau*, vol. 10, pp. 694-699.

[27] V. Chochev and K. Arabadzhieva, (2021). Fire modeling in a compartment railway passenger car. *Safety Engineering*, vol. 11, pp. 15–20.

[28] H. Chen Y. Feng, C. Zhang, L. Yu, Y. Shu, Y. Zhang, T. Meng, C. Jiang and F. Xu, (2024). Numerical Simulation of Passenger Evacuation and Heat Fluxes in the Waiting Hall of an Ultralarge Railway Station Hub. *Fire*, 7 :6.

[29] Y. Chen, C. Wang, J.B.H. Yap, H. Li and S. Zhang, (2020). Emergency evacuation simulation at starting connection of cross-sea bridge: Case study on Haicang Avenue Subway Station in Xiamen Rail Transit Line. *Journal of Building Engineering*, 29:101163.

[30] X. Jiaojiao and L. Jin, (2019). Simulation Study on Emergency Evacuation of Metro Stations in Fire Degradation Mode. *Journal of Physics Conference Series*, 1187: 5.

[31] Y. Diao and Z. Guo, (2021). Fire emergency evacuation model of light rail station based on BIM technology. *Journal of Physics Conference Series*, 1903:1.

[32] L. Lin, X. Meng, Z. Han and S. Xu, (2022). Emergency Evacuation Simulation of Urban Rail Transit Station. *Proceedings of the 2022 2nd International Conference on Computational Modeling, Simulation and Data Analysis CMSDA*, (pp. 60-65). IEEE.

[33] F. Jahedinia, M. Bagheri, A. Naderan and Z. Bahramian, (2023). Simulation of luggage-laden passengers' behavior in the evacuation process based on a floor field CA model case study: Tehran metro-rail transfer corridor. *Simulation*, 99: 7, pp. 681-701.

[34] Y. Lu, Y. Deng and S. Sun, (2024). Design for safety in metro station evacuation: a study of fire emergency evacuation behavior and simulation. *Engineering Construction and Architectural Management*, vol. 31, pp. 3479-3507.

[35] L. Li, L. L. Wei, M. Kinsey and A. Sun, (2018). HSTEAM - High Speed Train Evacuation Analysis Methodology. *Procedia Engineering*, vol. 211, pp. 18-27.

[36] X.-Y. Song, Y. Pan, J. Jiang, F. Wu and Y. Ding, (2018). Numerical Investigation on the Evacuation of Passengers in Metro Train Fire. *Procedia Engineering*, vol. 211, pp. 644-650.

[37] L. Yu, T. Deng, M.-N Wang, Q. Li and S. shuo. Xu, (2019). Passengers' evacuation from a fire train in railway tunnel. *International Journal of Rail Transportation*, vol. 7, pp. 159-172.

[38] K. Fridolf, E. Ronchi, D. Nilsson and H. Frantzich, (2019). The representation of evacuation movement in smoke-filled underground transportation systems. *Tunnelling and Underground Space Technology*, vol. 90, pp. 28–41.

[39] E.-S. Carlson, M. Kumm, A. Zakirov and A. Dederichs, (2019). Evacuation tests with elevated platforms in railway tunnels. *Fire Safety Journal*, 108: 102840.

[40] H.-P. Chang, H.-P Chang, S.-P Ho, C.-S Chen and T.-S Shen, (2016). The evacuation safety analysis of fire scenarios in the entire acoustic barriers of elevated Mass Rapid Transit System. *Tunnelling and Underground Space Technology*, vol. 56, pp. 65–69,

[41] A. Gulanur, C. Tian, Q. Xie, H. M. Shawkat and D. Liu, (2019). Simulation of Emergency Evacuation in a metro-rail transit station. *International Conference on Civil and Hydraulic Engineering*, 304: 3. IOPSCIENCE

[42] Z.-Y. Li, M. Tang, D. Liang and Z. Zhao, (2016). Numerical Simulation of Evacuation in a Subway Station. *Procedia Engineering*, vol. 135, pp. 616–621.

[43] Q. M. Si, J. Y. Li, X. Y. Guo, H. Wang, C. Y. Liu, (2024). Simulation of the Evacuation Strategy for an Air-Rail Intermodal Hub Station. *International Journal of Simulation Modelling*, vol. 23, (pp. 483–494). IJSIMM.

[44] B. Liu, C. Liu, P. Liu, T. He and H. Chen, (2020). Study on Fire Impact and Personnel Evacuation of Metro Trains in the Rail-and-Road Integrated Yangtze River-Crossing Tunnel. *Resilience and Sustainable Transportation Systems Selected Papers from the 13th Asia Pacific Transportation Development Conference,* (pp. 337-345). SPRINGER

[45] Y. Liu, W. Teng, Q. Sun, Y. Sun, S.Zhang and J. Shao, (2019).Fire and Evacuation Analysis Base on Light Rail Vehicles. *Proceedings of the 9th International Conference on Fire Science and Fire Protection Engineering ICFSEFPE*, (pp. 1-6). IEEE.

[46] N. de Los Rios, T. O'Dwyer, P. Petersen and S. Russo, (2017). The development of an emergency tunnel ventilation strategy for the WMATA system. *Proceedings of the 17th International Symposium on Aerodynamics Ventilation and Fire in Tunnels ISAVFT*, (pp. 631-644). BHR Group Limited.

[47] C. Biotto, J. Alston, P. Johnson and O. Dinsdale-Young, (2019). Unidirectional ventilation for steep metro rail tunnels. *Proceedings of the 18th International Symposium on Aerodynamics Ventilation and Fire in Tunnels ISAVFT*, (pp. 738-752). BHR Group Limited.

[48] A. Louie and S. Li, (2015). Coupling ventilation and egress analyses to design a safer station. *Proceedings of the BHR Group 16th International Symposium on Aerodynamics Ventilation and Fire in Tunnels, (pp. 315-326). BHR Group Limited.*

[49] M. Bakhshi, M. Partovi and A. Haghighat, (2023). Design of FRC precast segments for fire in light-rail tunnels. *Expanding Underground Knowledge and Passion to Make A Positive Impact on the World Proceedings of the Ita Aites World Tunnel Congress*, (pp. 1147-1156). Taylor & Francis

[50] K. J. Harris and R. Moreno, (2017). Compartmentation for train passenger fire safety. *Proceedings of the 17th International Symposium on Aerodynamics Ventilation and Fire in Tunnels ISAVFT,* (pp. 499-512). BHR Group Limited.

[51] S. A. Marsico, S. Li and A. Louie, (2019). Determination of cross-passage spacing from fractional effective dose analysis. *Proceedings of the 18th International Symposium on Aerodynamics Ventilation and Fire in Tunnels ISAVFT,* (pp. 661-675). BHR Group Limited.

[52] N. A. A. Tajedi, N.S.A. Sukor, M. A. M. Ismail and S.A. Shamsudin, (2017). Preparedness of fire safety in underground train station: Comparison between train operators in Malaysia with other operators from the developed countries. *Proceedings of the International Conference of Global Network for Innovative Technology and AWAM International Conference in Civil Engineering,* 1892: 060003. AIP Conference Proceedings

[53] F. Restel, Ł. Wolniewicz , A. Tubis, S. Haładyn, T. Kisiel and A. Kierzkowski, (2022). Identification of safety relevant activities of train crews using the Functional Resonance Analysis Method (FRAM). *Probabilistic Safety Assessment and Management (PSAM),* Art.no FR133. IAPSAM.

[54] B. Bassi, M. Deevy, J. Fletcher, M. Morgan, N. Nayan and S. Upadhya, (2016). Detailed fire safety design of subways for arson-initiated design fires: Innovation, coordination, implementation. *Proceedings of the Ita Aites World Tunnel Congress WTC*, vol. 1,(pp. 197-206).

[55] M. Pawlik, (2018).Electrified lines entering tunnels in Poland, safety aspects of the running with fire.*13th International Conference Modern Electrified Transport – MET'2017*, 180: 05003. Matec Web of Conferences

Notes on contributors

Ghizlane Aaboud received her engineering degree in Electromechanical Engineering from the National School of Mines in Rabat (ENIM), Morocco, in 2010. Currently, she is a Ph.D. student in Quality, Security, and Maintenance (QSM) at the Mohammadia School of Engineers (EMI), Mohammed V University in Rabat, Morocco. She can be contacted at: aaboudghizlane@gmail.com.

Mohammed Smouni received his engineering degree in Electrical Engineering from the Mohammadia School of Engineers in Rabat (EMI), Morocco, in 1987. Currently, he is a Ph.D. student in Quality, Security, and Maintenance (QSM) at the Mohammadia School of Engineers (EMI), Mohammed V University in Rabat, Morocco. He can be contacted at: smouniphd@gmail.com.

Taibi Saoudi received his engineering degree in Mechanical Engineering from the Mohammadia School of Engineers in Rabat (EMI), Morocco, in 1987. Currently, he is a Professor at the Mohammadia School of Engineers (EMI), Mohammed V University in Rabat, Morocco. He can be contacted at: taibi@emi.ac.ma.

Boudi Elmostapha received his engineering degree in Mechanical Engineering from the Mohammadia School of Engineers in Rabat (EMI), Morocco, in 1987. Currently, he is a Professor at the Mohammadia School of Engineers (EMI), Mohammed V University in Rabat, Morocco. He can be contacted at: boudi@emi.ac.ma.