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Risk Assessment for the Development of Emergency Scenarios for Tram Driver Training

Agnieszka A. Tubis *, **Artur Kierzkowski**, **Tomasz Kisiel**, **Ewa Mardeusz**, **Jacek Ryczyński** and **Łukasz Wolniewicz**

Department of Technical Systems Operation and Maintenance, Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, Wyspianskiego Street 27, 50-370 Wroclaw, Poland; artur.kierzkowski@pwr.edu.pl (A.K.); tomasz.kisiel@pwr.edu.pl (T.K.); ewa.mardeusz@pwr.edu.pl (E.M.); jacek.ryczynski@pwr.edu.pl (J.R.); lukasz.wolniewicz@pwr.edu.pl (Ł.W.)

* Correspondence: agnieszka.tubis@pwr.edu.pl

Featured Application: The presented research results can be implemented by transportation companies developing training requirements for personnel. The defined requirements and challenges for developing emergency scenarios provide critical guidance for training companies offering training based on modern teaching tools.

Abstract: (1) Background: This article presents research results from a project to develop a simulator and training program for tram drivers based on virtual reality tools. This article aims to present the research results on the risk assessment of adverse events to develop training scenarios for tram drivers. (2) Methods: The research methodology involved four steps, including the identification of adverse events based on interviews with experts, estimation of risk parameters, risk assessment using fuzzy logic, and risk evaluation to identify events recommended for the training program. (3) Results: Thirteen adverse events related to tram driving were identified and ranked according to the proposed classification. A risk assessment was then performed for the selected group of events using fuzzy logic models. The results made it possible to recommend situations that should be mapped in the virtual world as part of a tram driver training program. (4) Conclusions: The results made it possible to distinguish a group of events that should constitute the training area dedicated to tram drivers. Including the developed emergency scenarios in the training program allows employees to examine their reactions to stressful or dangerous situations and better prepare themselves for future duties.

Keywords: emergency scenarios; fuzzy logic; hazardous situations; tram driver training; VR tools

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1. Introduction

More and more training companies in Poland understand the need to change the forms of training for employees in the transport sector. Both trainers and trainees currently evaluate traditional forms of training as ineffective solutions. This is because conventional forms of training are theoretical, and practical skills are only acquired by the participant in the first weeks of work. This entails a high level of risk, as the lack of experience and practical skills exposes the employee and those around him to the consequences of his mistakes. For this reason, there is growing interest in training tools that use VR technology. The use of VR technology in training new employees and improving the skills of existing employees offers more significant opportunities to increase the effectiveness of learning theoretical issues and enhancing practical skills. This is mainly because the trainees learn faster and can test their skills in a safe virtual world rather than in the real world [1].

At the same time, the team's research indicates that driving simulators are now being used in many urban transport companies for training dedicated to tram drivers. Among the solutions used in the companies surveyed, driving simulators based on [2] were identified:

- Desktop structures in which the image is projected onto a flat external screen;
- Compact designs, in which the image is usually displayed on several independent monitors.

However, research indicates that the effectiveness of the solutions used is unsatisfactory. This is primarily due to the limited level of immersion present in these solutions. The trainee can observe the progress of the training task, but his or her level of 'immersion' in the operations being performed is low. This means that his or her level of engagement may be unsatisfactory while at the same time not being accompanied by full emotions and reactions to the training situations that arise. Applying a sufficiently high level of immersion through the implementation of dedicated VR solutions increases trainee engagement. It also provides the opportunity for more effective acquisition of practical skills needed in crises.

The ability to replicate crises represents a massive potential for developing VR-based tools. Never before have trainees had such opportunities to test their skills and emotions in dangerous or low-probability situations. Such situations in traditional training are most often presented to trainees only in theoretical terms due to the lack of opportunities to test them in practice. Attempting to reproduce them through practical exercises could endanger the lives and health of trainees or cause property damage. For this reason, trainees undergoing traditional training can only test their practical skills in standard situations and do not have the opportunity to rehearse emergencies. This can result in them being unable to take appropriate actions and behaviors during an emergency. VR training addresses these challenges. They make it possible to prepare trainees for their everyday duties and develop the proper behavior in dangerous situations. This, however, requires the development of appropriate training scenarios that replicate situations for which the risk index exceeds the acceptance level. Therefore, identifying such situations must be preceded by a proper risk analysis, highlighting the events that should be included in the training scenarios program for a given group of employees.

This paper presents the research results from the project 'Innovative training system for tram drivers based on a full-cabin simulator using cognitive science', funded by the National Center for Research and Development. The project aims to create a simulator in which the trainee is isolated from the outside world and immersed in a virtual world through the sense of sight (virtual projection of the environment) and the sense of hearing (sound projection), subjecting the participant to overload states. One of the stages of the research work was the preparation of training scenarios for hazardous situations, which should form part of the training program for motorists. Identifying such situations required detailed risk analysis and evaluation to identify incidents with a risk exceeding the acceptance level. This article aims to present the research results on the risk assessment of adverse events for developing training scenarios for tram drivers. The structure of the article is shown in Figure 1. The realization of the objective makes it possible to identify the following contributions:

- Identification and classification of adverse events related to tram driving;
- Risk assessment of undesirable events occurring in the work of a tram driver;
- Identification of hazardous situations that should be part of comprehensive competence training for tram drivers;
- Identification of challenges for developing emergency scenarios as part of VR training programs.

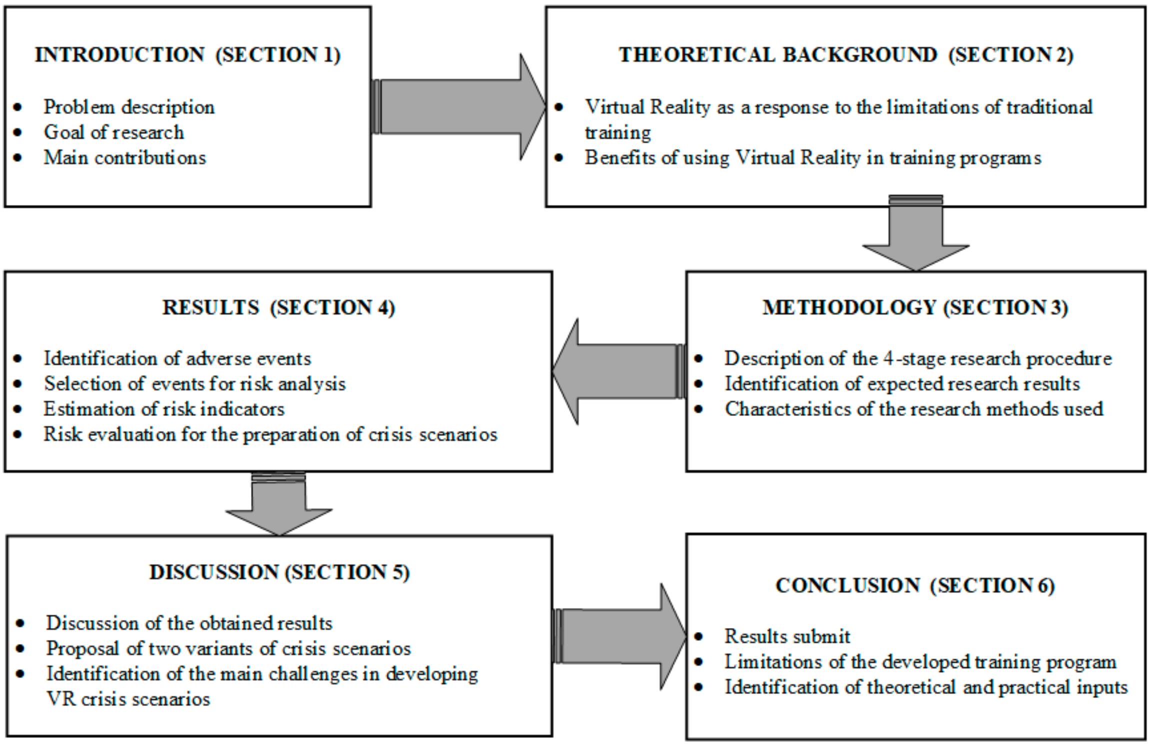

Figure 1. The structure of the article.

2. Theoretical Background

Several limitations burden traditional forms of training delivered in a real-world environment, the most common of which include the following [3]:

- Time-consumption—the large time requirements for organizing the actual training venue and for participants to get there;
- Cost-intensity—the costs of repeatedly preparing the actual training material and hiring professional trainers for small groups;
- Limited intuitiveness of activities and lack of attractive format—lack of visual cues, such as 3D animations, to illustrate skills and processes;
- Lack of opportunities for comprehensive skills training, particularly in emergency procedures and hazardous situations, which can only be safely trained in simulators.

For this reason, there is a growing demand for developing training programs that use virtual technology solutions. At the same time, we can observe the development of immersive technologies in visualization and interaction, which increases the attractiveness of VR training tools and the possibilities of their application in improving employee competencies. All these factors mean that the popularity of training conducted in the virtual world is increasing, and with it comes new challenges in preparing appropriate training scenarios.

Training tools using virtual reality technology are based on a digital environment that should represent real life. The level of this mapping is assessed through the prism of three attributes [4–7]:

- Immersion—the level of sensory fidelity provided by the VR system created;
- Presence—the subjective experience the user of the system experiences while in the created digital world;
- Interactivity—the extent to which the user can modify (influence) the VR environment in real time.

In the literature, VR systems are most commonly characterized by five components [8]: the VR engine, software and database, input/output devices, user, and tasks (training scenarios). An example diagram of a VR training system is shown in Figure 2.

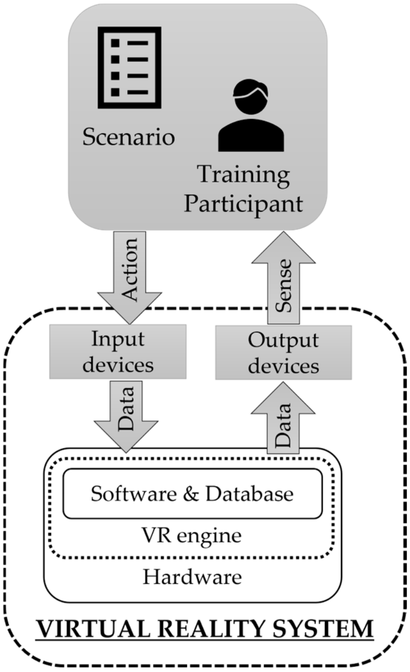

Figure 2. Virtual reality training system (based on [8]).

The virtual reality environment used is an essential element of the VR system under development. A review of the available solutions made it possible to distinguish the five types of environments analyzed as part of the team's research. These are presented in Table 1.

Table 1. Examples of virtual reality environments.

Name	Description
VR Motion Corp—RealDrive System [9]	A portable and cost-effective VR system that enables practical driver training in a controlled environment, offering realistic scenarios and high skill retention rates (the ability of trainees to retain and apply the skills they have learned over an extended period after training).
DReyeVR [10]	The system has been developed as an open tool for behavioral research. It allows dynamic scenario management, eye movement monitoring, and analysis of driver interaction in VR, making it a valuable tool for simulation and behavioral interaction research.
iDrive [11]	Desktop simulators for driver education. iDrive offers advanced simulators based on high-resolution screens and physical controls, allowing driving lessons to be taught in various conditions that are difficult to replicate in reality, increasing safety and reducing training costs.
DriveWise [12]	DriveWise has developed advanced VR simulators that offer an immersive and realistic driving learning experience. These simulators allow the environment to be tailored to specific needs, enabling participants to practice driving in various road and weather conditions that are difficult to replicate in actual driving. DriveWise also simulates emergency situations, allowing drivers to learn in a safe environment and improve their defensive skills and hazard perception. The ability to record and analyze data during the simulation allows instructors to provide effective feedback and improve participants' skills.
AVRT [13]	The system allows for realistic replication of emergencies in interactive scenarios, which is particularly useful in training emergency services and professional drivers. AVRT is distinguished by the ability to fully customize scenarios to meet specific training needs and record participant reactions, allowing accurate assessment of skills and identifying areas for improvement.

The development and implementation of a VR training system is a complex process. Usually, two phases are distinguished (preparatory and training), which consist of four stages of implementation, including system design (preparation), execution, implementation, and training. It is worth noting that most publications on the use of VR technology focus on the training phase. Issues concerning the work required in the preparation phase are less popular, even though the actual implementation of the tasks performed in the system during the training phase depends on them. Therefore, the research presented in [14], in which the authors proposed a new approach to preparing a VR training system for maintenance workers, deserves attention. Their proposed scope of tasks in the preparation phase is shown in Figure 3. Based on their results, it is possible to define guidelines for the individual tasks performed in the preparation and execution phase of the VR training system.

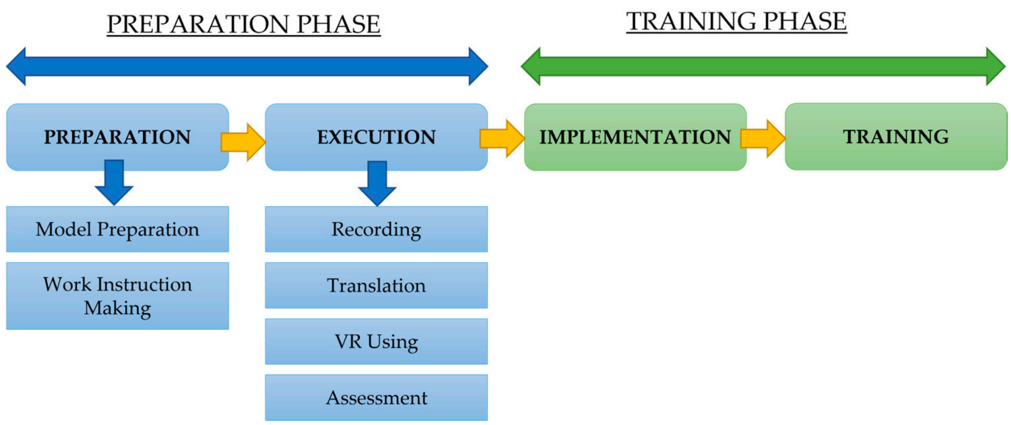

Figure 3. Virtual reality training preparation process (based on [14]).

In the preparation phase of the training system, two tasks can be distinguished [14]: (1) preparation of the model and (2) creation of working instructions. The prepared model is supposed to reproduce the reality in which the training tasks will be implemented. Therefore, it becomes necessary to design the behavior of the individual components of the system and the relationships between them. The components of the system may be other participants in the process, but also 'inanimate' elements. The correctness of the prepared model determines the level of immersion achieved. Then, the module for creating work instructions focuses primarily on describing the process and the sequence of actions to be taken. For this task, it makes sense to include an expert in the research work to assess the correctness of the mapped process. It can also provide a prototype of the correct actions taken (e.g., the correctness of gestures in the VR environment).

Developing training scenarios is an important element of the preparation phase not discussed in [14]. A training scenario is not just the model but a manual describing the project in progress. To capture the trainee's attention, it is necessary to build an appropriate story and include interactive elements that maximize the trainee's involvement. Therefore, creating an appropriate storyboard that depicts the key scenes and interactions in the training scenarios is necessary. Many script development companies and bloggers (for training and games) provide a wealth of material demonstrating how to prepare a storyboard (e.g., [15]). Among the main guidelines for creating training scenarios, it is worth mentioning the following [16]:

- Scripting branching scenarios. These scenarios allow trainees to make decisions and experience the consequences of their choices. This allows for effective revision of existing knowledge. At the same time, the scenarios themselves encourage behavioral change and provide opportunities to improve critical thinking.

- Using real-world challenges in training. Scenarios should include real-world situations and decision-making processes in the workplace. Simulating various real-world situations, particularly difficult or dangerous ones, allows trainees to gain practical experience in a safe, controlled environment.
- Taking into account different learning styles. Training simulations should be adapted to different learning styles if their developers want to maximize the effectiveness of the training process. Therefore, scenarios should include interaction with other senses to address the needs of different groups of trainees.
- Including elements of gamification. Incorporating gamification into training scenarios increases trainees' engagement and motivation. Methods such as points, rewards, and competition can increase the level of engagement in training by up to 80%.

Over the past 20 years, several studies have shown that VR training tools effectively acquire the required skills, which are then transferred to the real world [17–19]. Research by Krokos et al. [20] even suggests that participants remember more information and can better apply the knowledge they gained after participating in VR-based training than traditional skill development forms. However, research by Cooper et al. [21] has shown that VR-based training improves the effectiveness of skill acquisition/improvement, but on the condition that the simulated training environment is of high quality or includes additional task-relevant sensory cues. Also, research by Jensen and Konradsen [5] indicates that people using immersive HMD were more engaged and focused on their assigned tasks and more effectively acquired cognitive, psychomotor, and affective skills. However, the results of their study also confirm that the graphic quality of VR and awareness while using VR affect the level of immersion in the virtual world and the results' effectiveness.

Therefore, the effectiveness and speed of the learning process are determined by the level of immersion offered by a given training tool. This level determines the extent to which physical stimuli, such as light patterns or sound waves, are delivered to the human senses to create the illusion of the natural world [22]. Based on the level of immersion offered, there are currently three groups of virtual environments used in training tools [22–24]:

- Non-immersive virtual environment (Desktop VR)—training tools are based on scenarios presented on a conventional personal computer, and trainees perform assigned tasks using a mouse, keyboard, joystick, or touchscreen.
- Immersive virtual environment (IVR)—training tools are based on scenarios presented on several large-format screens or through a stereoscopic, head-mounted display unit. In addition, these systems are equipped with audio, haptic, and sensory interfaces that enhance the feeling of being inside a virtual world.
- Semi-immersive virtual environment (Fish Tank VR)—these systems are a post-medium form between the abovementioned environments. Training scenarios are implemented using a conventional monitor, but the system does not support sensory output. However, the tool supports head tracking and improves the feeling of 'being there' thanks to the motion parallax effect.

The research results described in this article relate to solutions using IVR. IVR enables the creation of a scalable tool that can provide a full range of sensory stimuli, access to a 360° virtual interface, and the ability to manipulate virtual objects during training [24,25]. It is also possible to isolate the trainee from the environment and uncontrolled external stimuli that distract them and prevent them from fully interacting with the digital world [26]. By using IVR, it is also possible to achieve, to a greater extent, the benefits of VR technology in training reported in the literature. These benefits are outlined in Table 2.

Table 2. Key benefits of using VR technology in training programs [27].

Benefit	Characteristics
Engagement	Immersive environments make users more interested and committed to their training.
Speed	Participants obtain and remember information attractively and efficiently, thus acquiring knowledge and skills faster.
Measurability	Completing tasks in a virtual environment makes it possible to obtain all the statistics required to allow the trainer to assess the participant's performance.
Reduction of work accidents	The possibility of implementing safe scenarios where participants can practice acquiring the necessary skills without risking their own or others' health and lives.
Personalization	Training scenarios can be adapted to the individual requirements of each trainee.
Reduction of costs	Reduction of expenses related to the infrastructure, materials, and personnel required for traditional training courses.

Summarizing the benefits reported in the literature regarding using VR solutions in training processes, the research findings are worth noting [28]. In this article, 184 publications on the use of virtual reality in training programs were analyzed. The results indicate that the most typical rationale for using VR in training is to reduce the limitations of traditional training methods, provide an immersive and attractive form of training, improve motivation, and increase participant engagement.

Despite the numerous benefits of using VR technology in training systems, the limitations of its use should also be kept in mind. The biggest problem associated with using VR tools in the training process is the potential for simulation sickness (also known as VR sickness or cybersickness [29]). Simulation sickness encompasses a set of symptoms occurring in a virtual reality user, i.e., general discomfort, fatigue, headache, eye strain, difficulty concentrating, increased saliva, sweating, nausea, blurred vision, and dizziness [30]. Simulation sickness is the body's reaction to discrepancies between visual information and proprioceptive and vestibular signals. The triggers of cybersickness fall into three categories [31]: individual, technological, and task-related factors.

A research challenge related to virtual reality is the occurrence of simulation sickness in a changing environment. Two different driving environments of an autonomous car were analyzed: driving on a country road and driving on a motorway [32]. In the second scenario, the user had to perform fewer maneuvers than driving on a dynamic country road. The study participants were verified by visualizing the electrogastrography (EGG) signals. In most cases considered in the study, signal amplitude and nausea were increased in the more dynamic driving environment. Changing the virtual reality environment leads to a recurrence of simulation sickness, as different training environments can elicit different sensory and physiological responses. In a study by Mourant and Thatcher [33], whose considerations are based on three driving environments, including motorway, rural, and urban, vehicle speed was shown to be a factor in the possibility of simulation sickness. Selected publications also highlight the impact of environmental complexity on cybersickness. In a helicopter flight simulation, two scenarios were verified, including a flight in cloudless conditions and a flight in stormy conditions, to determine the effect of simulation on cybersickness [34]. The results confirmed that the change in environment significantly increased the simulator sickness questionnaire (SSQ) total score from cloudless to stormy conditions. Increased tolerance to cybersickness is achieved by gradually adapting the user to the virtual environment. In [35], the optic flow strength of the virtual environment was improved, reducing cybersickness symptoms.

Also, the duration of time spent in the virtual environment is identified in the literature as a factor influencing the occurrence of simulation sickness. In [36], a clear positive correlation was found between the length of exposure time of virtual environment users and the scores obtained on the simulator sickness questionnaire (SSQ). Diversified times for individual ground handling tasks may increase simulator sickness under different scenarios. The longer time spent in virtual reality increases the number of episodes of simulator sickness, resulting in longer adaptation times. Stanney's et al. [36] work also highlighted that exposure time can affect the severity of adverse symptoms. It indicated a strong correlation between negative experiences with simulators and susceptibility to simulation sickness symptoms after exposure to virtual reality.

Also noteworthy is the research presented in [37], which evaluated a VR training tool dedicated to firefighters handling transport incidents with dangerous goods. Participants in the experiment were divided into two groups: a beginner group and an expert group. Assignment to each group was based on the self-defined level of experience with the procedures. This research showed that the expert group reported higher levels of overall cybersickness after performing two different scenarios compared to the novice group who performed one scenario. The above research may suggest a higher risk of illness during training on various vehicles and while performing different tasks.

Therefore, when deciding on the form of training, one should consider both the benefits of using VR technology and its limitations, which may prevent its full use in improving a given audience. Thus, attention should be paid to the conclusions formulated in [21], according to which VR technology is dedicated primarily to situations in which [21,28] (1) conducting training in real life is difficult or dangerous (the consequences of participants' mistakes would be too severe); and (2) training exercises would be impractical (emergency exercises) or too costly to be implemented in the real world.

For this reason, the research team decided to use virtual reality tools to develop a tram driver training program covering both basic skills training (implementation of standard duties) and behavior in abnormal situations (including dangerous situations). The virtual environment allows the trained personnel to 'get familiar' with an atypical situation, test their body's reactions to emerging emotions (primarily stress), and develop correct attitudes and behaviors in dangerous situations.

3. Methodology

The risk assessment of adverse events carried out was one of the critical elements of the research for preparing training scenarios. The scenarios were divided into two groups: (1) standard scenarios based on procedures describing the operational activities performed by the driver during driving and verifying knowledge of the applicable regulations; (2) emergency scenarios covering hazardous and undesirable situations identified based on the risk assessment carried out. The standard scenarios ensure that trainees acquire the required driving skills. In contrast, the crisis scenarios should enable future and existing drivers to develop appropriate behavior in dangerous situations. Therefore, the emergency scenarios are of particular importance. First, they are dedicated not only to new but also to experienced employees. Second, they can be part of training and continuous skills improvement programs for motorists with experience, for example, after a long-term shutdown. However, for this to be possible, a detailed risk analysis of the adverse events occurring is necessary, followed by an evaluation to identify those events that should be considered critical for inclusion in a motorist training program.

The research conducted to develop compelling emergency scenarios for motorist training was carried out in four stages, as shown in Figure 4.

The research was conducted in cooperation with selected urban transport operators operating tramway services. Representatives of these companies were included in a group of experts who participated in assessing the risk of adverse events, forming the basis for the prepared emergency scenarios. The total number of experts was 24. The experts included specialists responsible for vehicle fleet maintenance, long-serving motormen, driving instructors, motorman team leaders, and scientific researchers in urban and rail transport. This ensured that the identification of adverse events was comprehensive and based on knowledge of vehicle maintenance, management of motoring team members, and the individual experiences of those directly involved in the transport process. Therefore, the identification of undesirable events took into account the following sources of risk threatening the correct execution of transport:

- Incorrect management of the motoring team, affecting the quality of the performance of the assigned duties;
- Incorrect technical condition of the vehicle;
- The poor mental or physical state of the motorman;
- The poor state of the tram infrastructure.

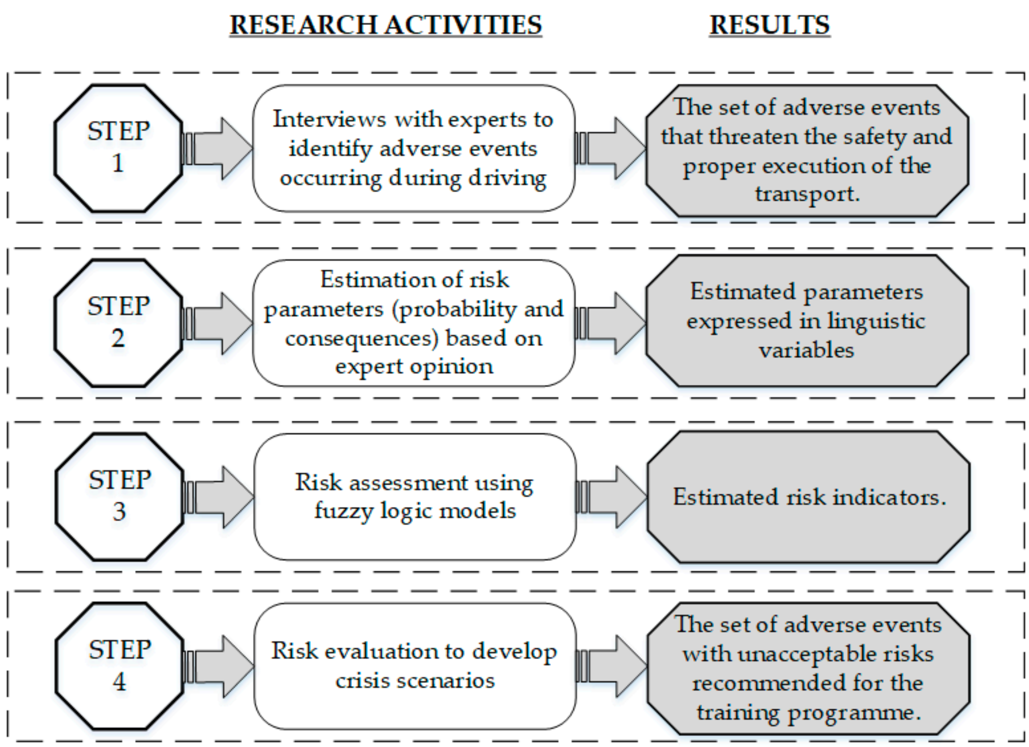

Figure 4. Research procedure.

In the second stage, values for the probability and impact of each identified adverse event were estimated based on expert opinion. The experts evaluated the level of both parameters based on a five-point scale in the form of linguistic variables described in Tables 1 and 2. The experts' opinions were collected through a direct structured interview. At this stage, those events for which estimated values of both risk parameters were low were eliminated from the identified adverse events.

The expert opinions became the basis for estimating risk indicators based on fuzzy set theory. This concept was used in the risk assessment process due to the use of uncertain data in the analysis, which is the subjective assessment of a given set of events by a group of experts. The applied scheme of the fuzzy inference system is presented in Figure 5.

The fuzzy inference system consists of three blocks:

- A blurring block, in which non-fuzzy input variables X are transformed, using membership functions, into fuzzy values $\tilde{X}$;
- An inference block, in which the fuzzy values of $\tilde{X}$, based on the rule base, determine the inference, which is in the form of a fuzzy linguistic variable $\tilde{y}$;
- A sharpening block, in which inferences from the linguistic variable $\tilde{y}$ based on membership functions, are transformed into an output fuzzy quantity y.

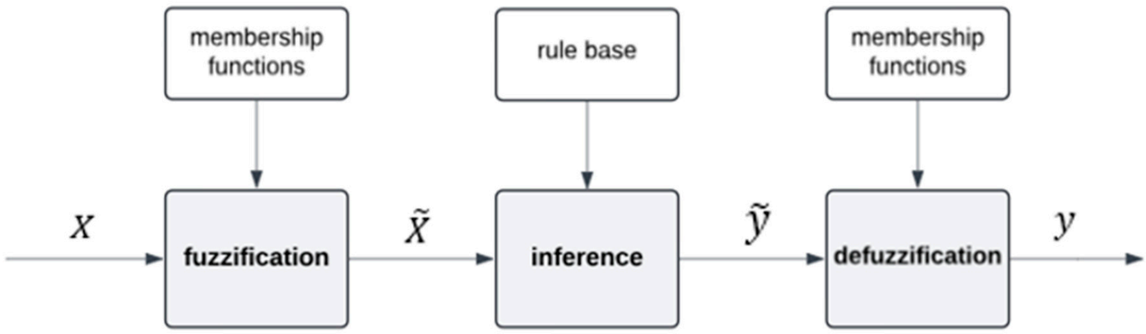

Figure 5. The sequence of implementation of individual calculation stages in the model using fuzzy sets.

The risk of training scenarios for tram drivers was assessed based on the following:

- Probability of scenario occurrence (PSO);
- Consequences of scenario occurrence (CSO).

The boundaries and shape of the membership functions used in the model were developed based on interviews with 30 experts, among whom were driving instructors, safety specialists, training and development specialists, and experienced tram drivers (experience of more than ten years). The limits of the membership function were statistically estimated using the parameters mean, standard deviation, and median minimum and maximum. The probability of scenario occurrence (PSO) membership function is based on a five-element scale: rare, unlikely, possible, very likely, and inevitable. A description of the linguistic variables for the PSO variable is presented in Table 3. The boundaries and shape of the PSO variable's membership function are presented in Figure 6.

Table 3. Description of the linguistic variables—probability of scenario occurrence.

Variable	Symbol	Description	Fuzzy Value
Rare	P1	Could happen, but probably never will	(0, 0, 0.15, 0.25)
Unlikely	P2	Not likely to occur in normal circumstances	(0.15, 0.25, 0.35, 0.45)
Possible	P3	May occur at some time	(0.35, 0.45, 0.55, 0.65)
Very likely	P4	Expected to occur at some time	(0.55, 0.65, 0.75, 0.85)
Certain	P5	Expected to occur regularly under normal circumstances	(0.75, 0.85, 1, 1)

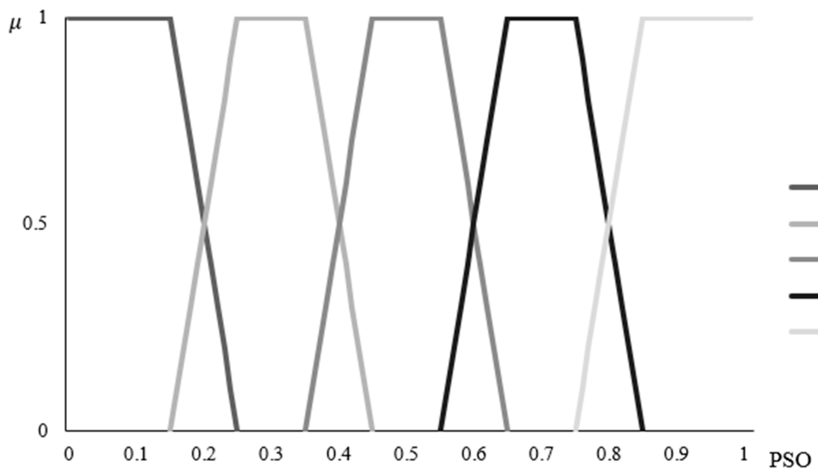

Figure 6. Input variable—probability of scenario occurrence.

The membership function of consequences of scenario occurrence (CSO) is based on a five-element scale: negligible, minor, moderate, high, and catastrophic. A description of the linguistic variables for the CSO variable is presented in Table 4. The boundaries and shape of the membership function of the CSO variable are presented in Figure 7.

Table 4. Description of the linguistic variables—consequences of scenario occurrence.

Variable	Symbol	Description	Fuzzy Value
Negligible	C1	No or negligible impact on the transport process	(0, 0, 1.5, 2.5)
Minor	C2	Minor disruption to the transport process resulting in a few minutes delay of the tram	(1.5, 2.5, 3.5, 4.5)
Moderate	C3	Temporary suspension of transport or risk to passengers' health and life	(3.5, 4.5, 5.5, 6.5)
High	C4	Temporary out-of-service of a vehicle, loss of health of persons (passenger, pedestrian, driver)	(5.5, 6.5, 7.5, 8.5)
Catastrophic	C5	Prolonged out-of-service or cancellation of the vehicle, long-term loss of health or life of persons	(7.5, 8.5, 10, 10)

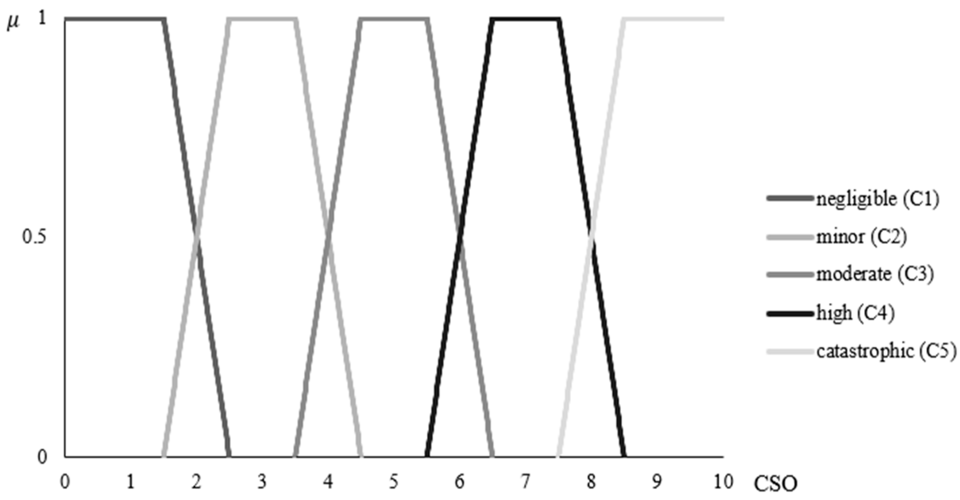

Figure 7. Input variable—consequences of scenario occurrence.

The inference block of the risk assessment model for motorist training scenarios is based on 25 IF-THEN rules. The evaluation model uses Mamdani implications and is based on MIN and MAX operators. The rule base of the assessment model is presented in Table 5.

Table 5. Description of the linguistic variables—consequences of scenario occurrence.

No.	PSO	CSO	RL
1	P1	C1	Low
2	P2	C1	Low
3	P3	C1	Minor
4	P4	C1	Medium
5	P5	C1	Medium
6	P1	C2	Low
7	P2	C2	Minor
8	P3	C2	Minor
9	P4	C2	Medium
10	P5	C2	Intermediate

Table 5. *Cont.*

No.	PSO	CSO	RL
11	P1	C3	Minor
12	P2	C3	Minor
13	P3	C3	Medium
14	P4	C3	Intermediate
15	P5	C3	Intermediate
16	P1	C4	Medium
17	P2	C4	Medium
18	P3	C4	Intermediate
19	P4	C4	Intermediate
20	P5	C4	High
21	P1	C5	Medium
22	P2	C5	Intermediate
23	P3	C5	Intermediate
24	P4	C5	High
25	P5	C5	High

The risk level (*RL*) membership function is based on a five-element scale: low, minor, medium, intermediate, and high. A description of the linguistic variables for the RL variable is presented in Table 6. The boundaries and shape of the RL variable's membership function are presented in Figure 8.

Table 6. Description of the linguistic variables—risk level.

Variable	Symbol	Description	Fuzzy Value
Low	R1	The occurrence of the event is almost impossible. The consequences are insignificant. No impact on traffic flow.	(0, 0, 1.5, 2.5)
Minor	R2	The occurrence of an event is possible with limited/not significant consequences—little impact on traffic flow.	(1.5, 2.5, 3.5, 4.5)
Medium	R3	The probability of an event occurring is almost inevitable. The consequences are minor or negligible, or the consequences are high. However, the event is unlikely to occur.	(3.5, 4.5, 5.5, 6.5)
Intermediate	R4	An almost certain or certain event that occurs with minor consequences or the unlikely event that may have critical consequences.	(5.5, 6.5, 7.5, 8.5)
High	R5	There is almost certain to be an event with the most severe consequences, which in the real world prevents the driver from temporarily carrying out his work.	(7.5, 8.5, 10, 10)

The sharpening block of the risk assessment model for driver training scenarios uses the center of gravity method. The output value is determined from the formula [38]:

$$y = \frac{\int \mu_A\left(\widetilde{y}\right) \times d\widetilde{y}}{\int \mu_A\left(\widetilde{y}\right) d\widetilde{y}} \quad (1)$$

where y—defuzzified output; $\mu_A\left(\widetilde{y}\right)$—the aggregated output MF; and $\widetilde{y}$—the universe of discourse.

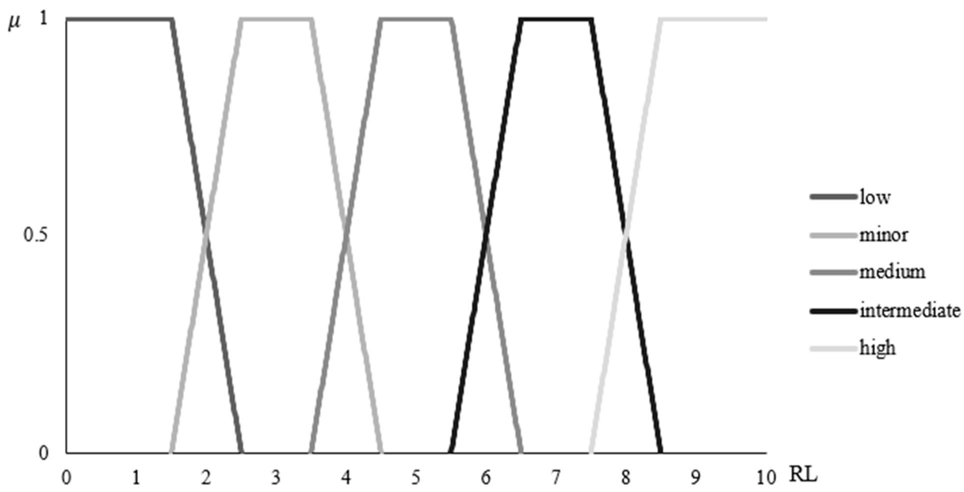

Figure 8. Input variable—risk level.

A schematic of the risk assessment model of training scenarios for tram drivers is presented in Figure 9.

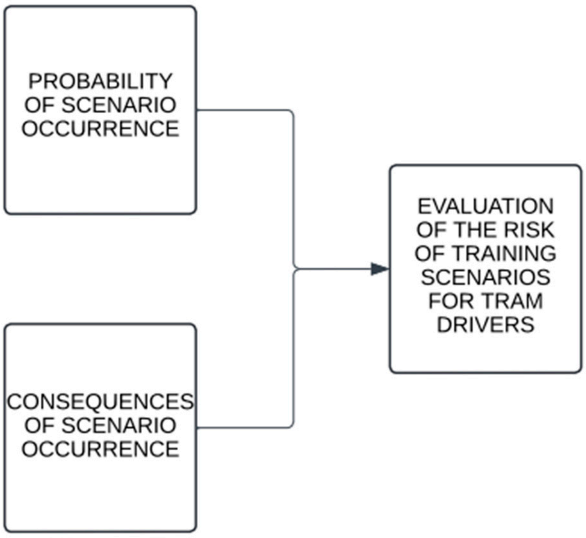

Figure 9. Diagram of the risk assessment model of training scenarios for tram drivers.

The estimated risk indicators were adopted for evaluation to determine undesirable events that should be considered when preparing emergency scenarios. The basis of the evaluation process is determining the risk acceptance level. Based on brainstorming among experts, it was assumed that the risk acceptance level should be at most four. This means that for all adverse events with a risk index higher than four, emergency scenarios should be developed as part of the driver training program.

The use of fuzzy logic, compared to other risk assessment methods, has several advantages, especially in the case of the analysis of uncertain and subjective data, such as those that formed the basis of the risk assessment in the presented study. Traditional risk analysis models based on classical probabilistic methods require precise and unambiguous input data, often unavailable or difficult to measure in actual conditions. Meanwhile, in applications such as assessing training scenarios for tram drivers, the data may be characterized by a high level of uncertainty or subjectivity, resulting from the need to rely on expert assessments or historical events, which may not be fully representative of all possible scenarios. Fuzzy logic allows for introducing vague variables into the risk assessment process, which increases the flexibility and adaptability of the model concerning the actual context of risky situations [39,40]. This allows for a more precise representation of the real conditions in which tram drivers may find themselves while performing their duties, which promotes a better representation of dynamic and often ambiguous situations. In the case of the conducted research, fuzzy logic enabled multi-level expert analysis of the probability of occurrence and potential consequences of adverse events, a key element of risk assessment in VR simulation-based training.

Fuzzy logic also improves the accuracy and usability of risk assessment results by creating more scalable and realistic training scenarios. Research has shown that fuzzy logic is particularly compelling in modelling situations with many unmeasurable or uncertain variables, making it an ideal tool for analyzing risk in complex transport systems [41,42]. In the case of tram driver training, where risk may come from various sources, such as external factors, human errors, and technical system failures, fuzzy logic allows for a comprehensive representation of these factors, enabling the identification of situations requiring special training attention.

Using methods based on fuzzy sets also brings benefits to optimizing the training process. FL models allow for more accurate classification of events into risk levels, which enables better prioritization of training scenarios and focus on situations with the highest potential for health and life hazards. For training drivers to be prepared for crises such as collisions, accidents involving pedestrians, or technical problems, implementing fuzzy logic provides an effective tool for developing simulation scenarios that not only represent real threats but also enable the development of competencies, enabling an effective response to unforeseen situations.

4. Results

As part of step 1, the experts distinguished 52 adverse events that can occur during a motorist's work. These events were divided into three groups according to the source of the risk. Figure 10 shows each group and the number of incidents identified and classified into each group by the experts.

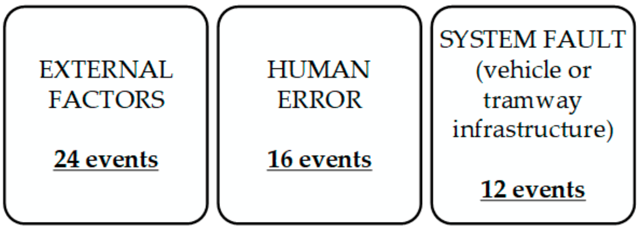

Figure 10. Number of sets of adverse events by risk source.

Then, for each event, the experts estimated values for the two metrics underpinning the risk analysis, including the probability and consequences of the adverse event. This made it possible to identify those events for which both likelihood and consequences were estimated by the experts at a very low level and risk was assessed at a low level. The pairs are described as follows:

- Probability: *rare*—Consequences: *negligible*
- Probability: *rare*—Consequences: *minor*
- Probability: *unlikely*—Consequences: *negligible*

Undesirable events with probabilities of occurrence or consequences that are close to zero (they have never occurred in systems known to the experts or their consequences are hardly noticeable to the participants in the transport process) were also rejected. Eliminating all the cases defined above made it possible to reduce the number of adverse events accepted for analysis to 13. These scenarios are presented in Table 7.

Table 7. Scenarios recommended for analysis.

Scenario	Adverse Events
AE1	Derailment
AE2	Collision
AE3	Man at trackside under the influence of intoxicants
AE4	Vehicle damage
AE5	Fire at the track (e.g., grass burning)
AE6	Fatal run-over of a pedestrian/bicyclist
AE7	Overturning a passenger in the vehicle—sudden braking
AE8	Passenger door slamming
AE9	Overhead line damage (severance, pole sway)
AE10	Overspeeding
AE11	Misrouting
AE12	Entering a vehicle at a closed signal
AE13	Incorrect driving technique—sudden braking/acceleration

A risk assessment procedure was carried out using the described fuzzy logic model for the events defined in this way. Figure 11 shows an example of the rule base for the vehicle damage event (Table 5—event AE4), for which the probability of occurrence was 0.35, and the consequences were estimated at level 3.

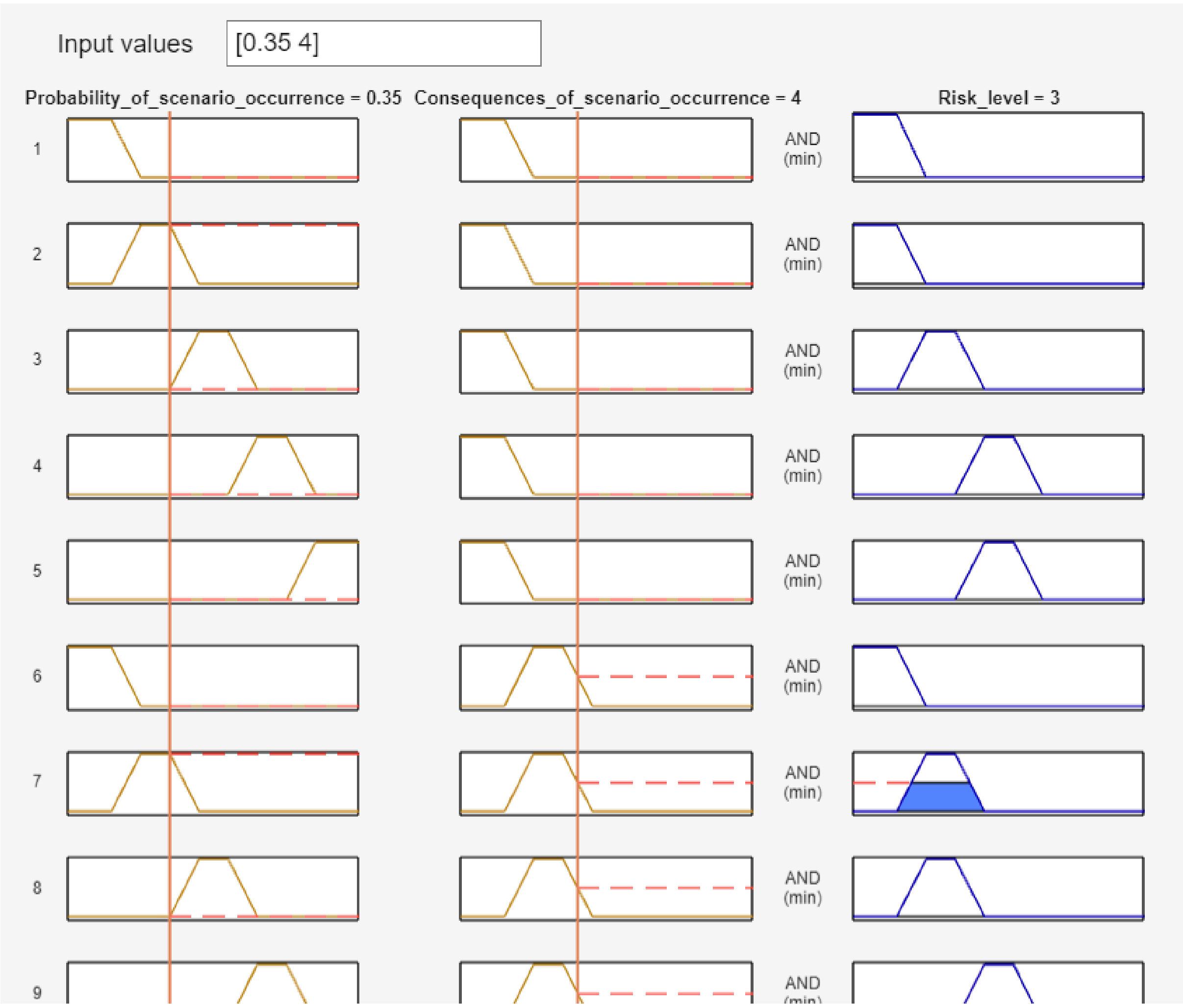

Figure 11. Example of calculating the risk level using the model for the AE4 scenario.

The assessment procedure was carried out according to the adopted model, and the results obtained from step 3 are presented in Table 8. Figure 12 presents the control surface for the proposed risk assessment model in the MATLAB environment.

Table 8. The results of the risk assessment for all analyzed scenarios were obtained.

Scenario	P (Fuzzy)	P (Crisp)	C (Fuzzy)	C (Crisp)	Risk Level
AE1	P1	0.10	C5	8.00	5.00
AE2	P2	0.30	C4	7.00	5.00
AE3	P2	0.15	C4	7.50	5.00
AE4	P3	0.35	C3	4.00	3.00
AE5	P2	0.12	C4	6.00	4.00
AE6	P1	0.08	C5	8.50	5.00
AE7	P3	0.37	C4	7.40	5.44
AE8	P4	0.79	C4	5.60	7.22
AE9	P3	0.58	C3	3.80	4.43
AE10	P3	0.60	C3	3.70	4.51
AE11	P2	0.36	C2	1.80	1.70
AE12	P2	0.37	C3	4.00	3.58
AE13	P3	0.59	C3	5.70	5.82

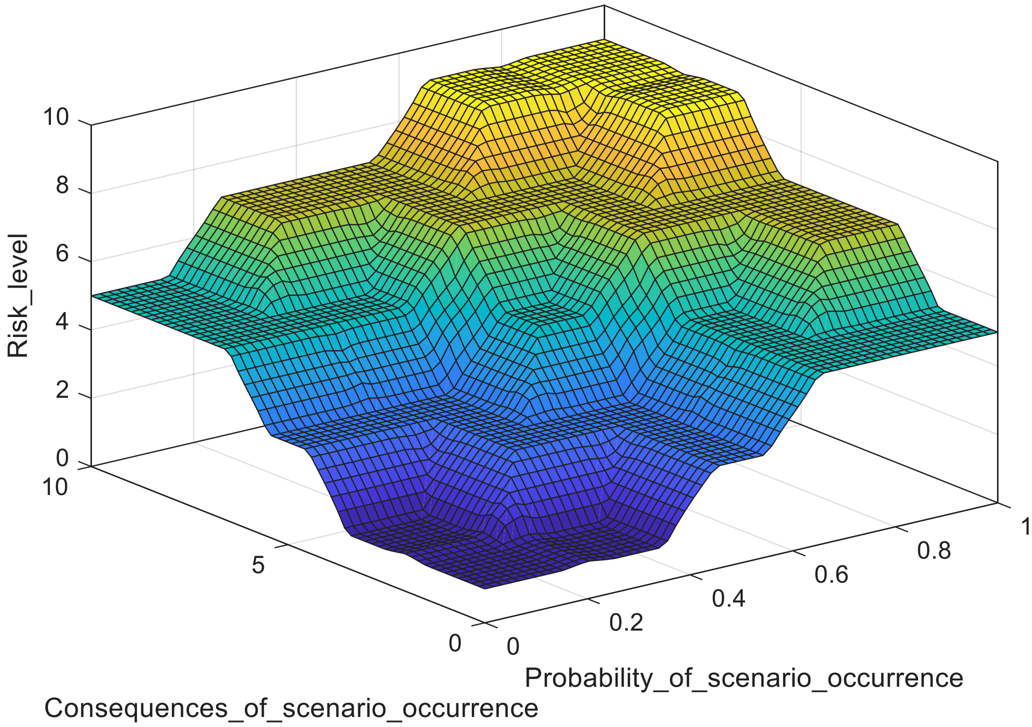

Figure 12. Model control surface. Where: blue—low risk level, green—medium risk level, yellow—high risk level.

Then, based on the brainstorming carried out in the expert group, the risk acceptance level was determined, which was set at RLA = 4. This means that all events with a risk level that is higher than the determined RL level will be recommended for the emergency scenario preparation process. Figure 13 indicates the affiliation of all analyzed adverse events to both risk groups.

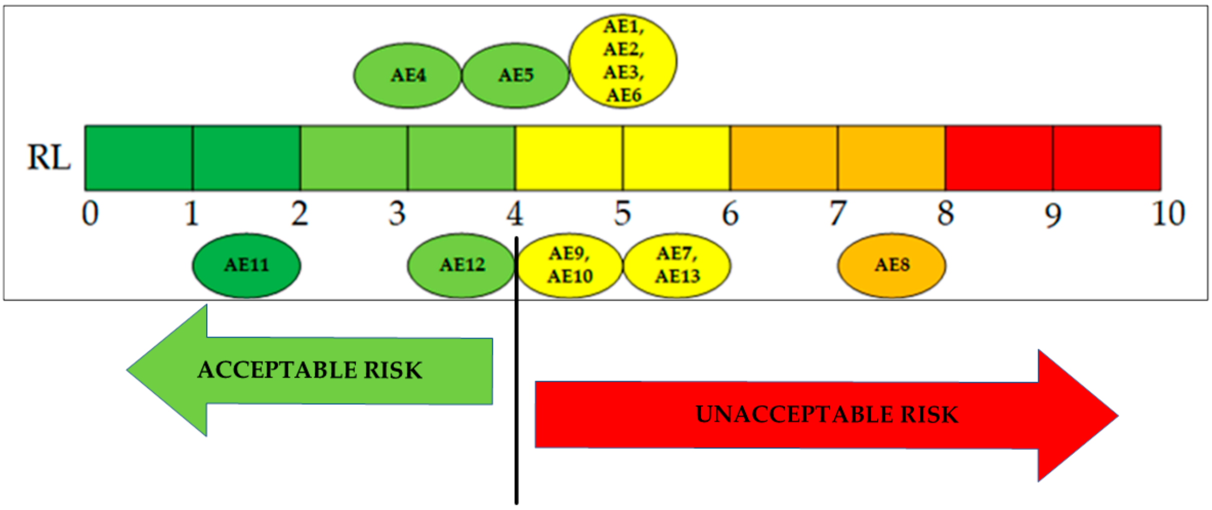

Figure 13. Classification of events according to risk acceptance level.

A significant issue when building crisis scenarios is the source of the risk involved. For this reason, the affiliation of the highlighted scenarios to the groups shown in the figure (groups) is also essential for their proper preparation. A classification of the scenarios identified for implementation into the distinguished groups is presented in Table 9.

Table 9. Classification of scenarios according to risk sources.

External Factors	Human Error	System Fault
AE3	AE1; AE2; AE6; AE7	AE4
AE5	AE8; AE10; AE11	AE9
	AE12; AE13	

This classification is critical for developing and implementing the prepared emergency scenarios in the VR training programs being developed. There will be different scenarios for incidents caused by the driver's fault, which may be due to illness, lack of concentration, etc., and different scenarios will be constructed for incidents whose source of risk is the environment (e.g., the behavior of other road users), the condition of the vehicle, or the transport infrastructure.

5. Discussion

The results of studies on virtual reality in training systems indicate numerous advantages over traditional forms of training [27,43–47]. A literature review by Chang et al. [44] confirms the efficacy and social validity of training VR solutions, including the seamless transfer of target skills from the virtual to the real world. This research also confirmed that disability and age are not significant barriers to acquiring target skills using VR tools, provided that the solutions are adapted to the needs of potential users. At the same time, in our opinion, the most significant potential of VR training tools relates to the possibility of using them in scenarios that would be very difficult, and often even impossible, to implement in real-world conditions. This benefit is also pointed out by the authors of other studies describing the implementation of developed VR tools [48].

Ongoing research shows that, alongside motion sickness, a critical aspect of training system implementation is the availability of VR tools. The limited availability of a single simulator proved a significant challenge in preparing the training system. Introducing smaller, compact VR simulators for initial training phases is proposed to meet the training needs of a larger group of tram drivers while minimizing costs. These compact simulators allow new drivers to familiarize themselves with key scenarios and interactions without needing the full-size simulator. This solution lowers costs and reduces the waiting time for access to the primary simulator. In addition, effective scheduling of the large simulator through a reservation system could prioritize participants ready for advanced scenarios, ensuring an even distribution of access and increasing resource efficiency. Developing differentiated training paths tailored to participants' skill levels offers another key approach to optimizing simulator availability. New tram drivers could start training on smaller simulators, progressing to advanced sessions only after mastering basic skills. Furthermore, recording and analyzing sessions on compact simulators allows for early assessment of participants' competencies, enabling efficient allocation of time on the large simulator to those fully prepared for high-risk scenarios. Implementing these strategies enables a more effective and scalable use of the VR training system, allowing for the gradual development of tram drivers' skills while maintaining cost control and maximizing the utility of available resources.

The possibility of transferring the real world into a virtual environment with the stimuli affecting the trainee offers enormous possibilities regarding the reproduction of various complex and dangerous situations. This provides the potential to develop training programs with additional elements that were impossible to implement in traditional forms. Above all, it is possible to prepare training scenarios, the execution of which in the real world would expose the trainee and others to loss of health or life (e.g., hit-and-runs, collisions). In addition, in the developed training scenarios, it is possible to generate random situations, the occurrence of which is difficult to ensure in the course of traditional training (e.g., difficult weather conditions such as ice on the tracks, fire near the tracks, or the appearance of a person under the influence of intoxicants near the tracks). It may also be part of the training program to make the participant aware of the consequences of their actions by including in the training scenario events that result from human error (e.g., a passenger being knocked over in a vehicle, a passenger being slammed by a door). The identified opportunities for creating new training programs based on VR technology demand a change in the approach to creating scenarios. This is because their preparation is associated with entirely different challenges than those encountered in developing standard training scenarios and improving the basic skills of trainees.

Training scenarios should be based on a risk assessment that identifies the relevant adverse events in a tram driver's work and allows for a risk assessment of their occurrence. Our research has shown that the number of such events is very high, but it is not reasonable to include all of them in training programs. Above all, preparing training scenarios for events with a very low probability of occurrence and insignificant consequences is economically unjustified (costs of preparing and implementing the scenario versus benefits of the acquired skills). In addition, too many developed scenarios would generate a very high time commitment for participants completing an entire training cycle. Implementing a training program based on many scenarios is unacceptable because staying too long in the virtual world can cause simulation sickness in trainees. Therefore, limiting the number of scenarios to events with unacceptable risks of occurrence is necessary. For this reason, the risk evaluation stage is critical to identify those adverse events that decision-makers consider required to reproduce in the virtual world.

The research results also proved that the nature of the occurring event is critical when creating emergency scenarios. The classification of adverse events adopted in the research, based on the source of the occurring threat, became a guideline for creating two variants of emergency scenarios.

- OPTION 1: Training scenarios that replicate hazardous situations. They aim to enable the trainee to acquire new skills for dangerous situations. The trainee can learn about the emotions accompanying a specific crisis and develop correct behavior patterns per the established procedure. Option 1 is mainly assigned to scenarios describing events for which the threat comes from the environment or the technical system.
- OPTION 2: Scenarios which extend the standard training scenario to include an emergency situation. They aim to inform the trainee of the consequences of wrong

decisions and mistakes. The trainee can learn about the emotions accompanying a specific emergency and develop behavior to limit the consequences. The main scenarios that qualify for Option 2 are those describing incidents where the human factor is the source of the risk.

In the case of Option 2, the training scenario is an extension of the baseline scenario, and its activation should depend on the mistakes made by the trainee. However, it is possible for a trainee who wishes to test their skills in hazardous situations to activate an emergency scenario consciously. These scenarios can also be used to work on the emotions accompanying the driver in difficult situations, where the attitude and reactions of the driver determine the amount of consequences of an adverse event.

Developing multi-variant training scenarios makes identifying a dedicated training delivery scheme necessary. It is necessary to establish the sequence in which the different groups of scenarios are implemented to ensure the effectiveness of the required training. Motorists can only implement emergency scenarios after acquiring the relevant competencies for which they are trained in the base scenarios. A lack of the knowledge and skills needed to implement standard procedures may result in inappropriate emergency responses or unconsciously unsafe actions. For this reason, new motorists must first acquire the baseline skills to improve their competence further. Crisis scenarios should also be carried out in a set order. It makes sense for the trainee first to become aware of the consequences of their mistakes and only then to acquire new skills for dangerous situations (already aware of the consequences of specific actions). The recommended sequence of scenarios in the developed driver training system is shown in Figure 14.

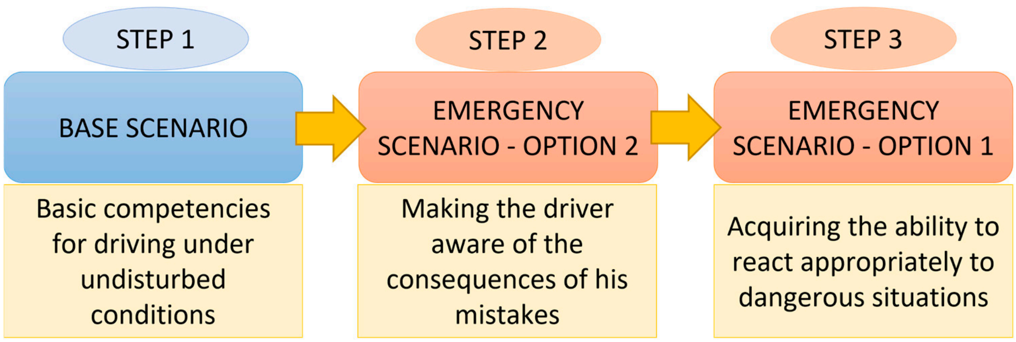

Figure 14. Recommended sequence of scenarios in the developed driver training system.

The presented results of the conducted research focus on assessing the risk of occurrence of undesirable events in a motorist's work, which should form the basis for the developed emergency scenarios implemented in motorist training programs using VR technology. However, their critical analysis makes it possible to formulate the challenges that occur in connection with the creation of training programs, taking into account not only the improvement of basic driving skills but also the acquisition of skills necessary in unusual and dangerous situations (including the formation of correct behavior and control of emotions). The main challenges highlighted include the following:

- Multi-criteria identification of undesirable events will enable the creation of a comprehensive set of events to form the basis of the risk analysis to be carried out.
- Risk assessment is based on reliable data and ensures the required level of objectivity of the results (especially in the case of events not supported by historical data).
- The selection of adverse events to be mapped in virtual reality is based on rational considerations (e.g., level of risk acceptance and high social consequences).
- The training program for emergency scenarios should be adapted to the psychophysical capabilities of the trainees.

The above challenges should be considered essential in the work of the team responsible for the development and implementation of emergency scenarios. The correct implementation of industrial work (e.g., expert research, quantitative analysis, process analysis) is critical for the accurate preparation of training programs and the selection of scenarios, the implementation of which will allow for the comprehensive acquisition of the skills required in the work of a tram driver.

6. Conclusions

This paper aims to present the results of a study on risk assessment of adverse events to develop training scenarios for tram drivers. The research used a four-stage methodology that included expert panels and a risk analysis model based on fuzzy logic. Based on the procedure, 13 adverse events were singled out, and their risk indicators take on a value that qualifies them for inclusion in training programs for tram drivers. At the same time, these events were grouped according to the distinguished event categories based on the identified source of the occurring risk. The defined event categories also guide the creation of emergency scenario variants. It should be noted that the research identified two options for integrating emergency scenarios into training programs. In addition, the final inference made it possible to define the main challenges of creating emergency scenarios for developing training programs using VR.

A limitation of the presented results is that data from existing tram systems in Poland were used in the analysis. The authors tried to consider the different specificities of urban transport systems in their research by including experts from different cities. However, limiting the analysis to the territory of one country results in a lack of consideration of a wide range of other potentially hazardous situations that may occur in tram systems located in different countries or on other continents. This makes the training programs developed mainly applicable to the chosen country. Of course, this local character can also be reinforced by including region-specific road rules and regulations in the training programs. However, the comparative analysis of risk assessment results for creating emergency scenarios for tramway systems operating in different locations worldwide is an exciting direction for future research.

The results presented provide insights for the scientific and business community. From a scientific perspective, the article provides knowledge regarding the proposed research methodology to create emergency scenarios for VR training. The results also indicate challenges researchers should consider when developing and implementing emergency scenarios in training programs. For the industry, an important issue is the identified adverse events that experts recommended for inclusion in training programs. The results presented in the article also demonstrate the potential of training using VR technology. Therefore, they can incentivize managers to change their workforce's skill acquisition and development forms.

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