Improving Human Reliability Analysis for Railway Systems Using Fuzzy Logic

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 13, 2021, accepted September 4, 2021, date of publication September 13, 2021,
date of current version September 23, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3112527

Improving Human Reliability Analysis for Railway Systems Using Fuzzy Logic

LORENZO CIANI[1], (Senior Member, IEEE), GIULIA GUIDI[1], (Student Member, IEEE), GABRIELE PATRIZI[1], (Student Member, IEEE), AND DIEGO GALAR[2,3]

[1]Department of Information Engineering, University of Florence, 50139 Florence, Italy
[2]Division of Operation and Maintenance Engineering, Luleå University of Technology, 97187 Luleå, Sweden
[3]Industry and Transport Division, Tecnalia Research and Innovation, Miñano, 01510 Araba, Spain

Corresponding author: Lorenzo Ciani (lorenzo.ciani@unifi.it)

ABSTRACT The International Union of Railway provides an annually safety report highlighting that human factor is one of the main causes of railway accidents every year. Consequently, the study of human reliability is fundamental, and it must be included within a complete reliability assessment for every railway-related system. However, currently RARA (Railway Action Reliability Assessment) is the only approach available in literature that considers human task specifically customized for railway applications. The main disadvantages of RARA are the impact of expert's subjectivity and the difficulty of a numerical assessment for the model parameters in absence of an exhaustive error and accident database. This manuscript introduces an innovative fuzzy method for the assessment of human factor in safety-critical systems for railway applications to address the problems highlighted above. Fuzzy logic allows to simplify the assessment of the model parameters by means of linguistic variables more resemblant to human cognitive process. Moreover, it deals with uncertain and incomplete data much better than classical deterministic approach and it minimizes the subjectivity of the analyst evaluation. The output of the proposed algorithm is the result of a fuzzy interval arithmetic, α-cut theory and centroid defuzzification procedure. The proposed method has been applied to the human operations carried out on a railway signaling system. Four human tasks and two scenarios have been simulated to analyze the performance of the proposed algorithm. Finally, the results of the method are compared with the classical RARA procedure underline compliant results obtain with a simpler, less complex and more intuitive approach.

INDEX TERMS Fuzzy logic, human factors, reliability engineering, railway engineering, maintenance.

I. INTRODUCTION

Railway engineering is a complex field in which many aspects of work throughout the complete system life cycle are performed by human operators. Starting from design and construction of the system up to the functioning, management and maintenance, human operators play a fundamental role in the life cycle of several railway-related systems [1], [2]. Several papers and technical reports [3]–[5] agree that lots of railway accidents are caused by human error or by the combination of human errors with hardware/software failures. Furthermore, also the European standard EN 50126 [6] which covers the topic of Human Reliability Analysis (HRA) in railway engineering points out the necessity of a proper Human Error Probability (HEP) evaluation since it severely contributes to the overall RAMS (Reliability, Availability, Maintainability, Safety) parameters of the system under study.

Catastrophic disasters and dangerous accidents are the most evident results of human errors. However, trivial human errors that lead to minor accidents without safety implications are quite common [7]–[9]. Studying the reliability of a system (either a mechanical or an electrical one) is absolutely necessary to take into account every operating conditions that affect the hardware performances, such as temperature excursions, relative humidity, mechanical vibrations, thermal and mechanical shocks and so on [10], [11]. Quite the same, the operative conditions of the human operators must be taken into account during the assessment of the Human Error Probability (HEP). Internal and external factors such

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott.

as ergonomics of the workstation, time available to complete the task, microclimate, level of stress etc. deeply affect the behavior of the operators [12].

Despite several HRA techniques are available in literature, only one method specifically developed for railway engineering has been published. The Rail Safety and Standards Board (RSSB) proposes a customized technique called Railway Action Reliability Assessment (RARA) in 2012 to evaluate the human error probability in railway field [13]. RARA method is extensively used in railway engineering since it is the only approach widely recognized in this field. However, several criticalities could be found in this technique. The first one is the impact of subjectivity of the analyst that performs the evaluation, which is not taken into account. The second one is the difficulty and complexity required for the assessment of the numerical values which represent the impact of each external factor that influence the human performances. Therefore, the quality of the estimation is extremely related to the experience of the analyst performing the assessment. Trying to solve these needs, this research aims at finding an innovative HRA method specifically developed for railway engineering applications which must be able to solve the major drawbacks of the RARA method available in literature, namely the impact of analyst subjectivity and the complexity of a numerical assessment of the influence factors. The approach proposed in this work is based on fuzzy logic and interval arithmetic to estimate the HEP of railway-related task with the aim of reducing the drawbacks of the classical RARA method. More in detail, the proposed approach simplifies the assessment of the HEP by means of linguistic variables to describe both the probability of error and the affect level of each internal and external factor. In this way, it is possible to develop a simple and effective tool for HEP assessment which minimizes the subjectivity and the impact of analyst experience. Fuzzy sets have been used as human reliability ratings because classical ratings may be ambiguous, uncertain, and hardly represented with a crisp number, while linguistic variables may provide the optimal solution to solve such problems.

The major contributions of the proposed method are the following:

- Introduction of an innovative HRA method specifically developed for operator tasks in railway engineering which uses fuzzy logic to estimate the HEP.
- Proposal of a RARA-based methodology able to solve two of the major problems of the classical RARA: the analyst subjectivity and the difficulty and complexity of a numerical assessment of the affect level.
- Validation of the results achieved on a real case study through a comparison with RARA method.

The rest of the paper is organized as follows: section II presents a detailed literature review regarding HRA, Section III presents the proposed fuzzy-based approach along with the developed tool, in section IV the proposed method is applied to a real case study and finally Section V presents the results validation through comparison with an existing HRA method.

II. LITERATURE REVIEW

Starting from 1970 Human Reliability Analysis (HRA) has been extensively studied introducing many different techniques for Human Error Probability (HEP) estimation. Each method could be classified into three categories:

- First-generation techniques are HRA milestones. They are simple approaches which consider a human being the same as an electric/mechanic component (i.e. it is only capable to succeed or fail). The HEP is calculated weighting the base error probability of the task with some factors called Performance Shaping Factor (PSF) [14], such as available time, stress, and working time [15], [16]. Generally, these methods classify errors as omission (when the operator fails to carry out a task) or commission (when the operator carries out a task incorrectly or do something that is not required). Moreover, simple cognitive models are used such as the Rasmussen operator performances classification (skill-based, rule-based or knowledge-based).
- Second-generation techniques introduce cognitive models and focus on the role of the context in the HEP evaluation. The aim of these methods is to include the human cognition (mental processes such as thinking, remembering, problem solving etc.) within the analysis of human performances.
- Third-generation techniques introduce simulator to generate data for the analysis. These methods aim at developing new HRA methods or modifying existing HRA techniques to consider the dynamic progression of human behavior which leads to a human error. The dynamic models used to estimate human behavior represent a fundamental aspect in modern HRA techniques.

Table 1 summarizes the main HRA techniques of each generation pointing out the field of application, the year of publication and the central points of each method. As it is possible to see in Table 1, most of the techniques has been developed for nuclear industry. Despite this, human reliability is a central point in many different fields of application where human errors could lead to dangerous accidents and hazardous conditions. One of this fields is the railway industry which requires an accurate human reliability analysis in compliance with the European standard EN 50126 [6]. According to the latest UIC (International Union of Railway) safety report 2020 [5] human factor is the second cause of railway accident after external causes (such as trespassing, pedestrian on public railway, weather, etc.) accounting for the 3.7 % of all accidents. Consequently, the estimation of the HEP in railway could provide several benefits to avoid dangerous accidents. As a matter of fact, only few works in recent literature deals with human reliability analysis in railway engineering.

In [32] the probability of failure in the communication actions between driver and signaler have been analyzed.

TABLE 1. State of the art of human reliability analysis: summary of the main techniques.

Classification	Technique	Field	Year	Main points
First Generation	**THERP** [17] (Technique for Human Error Rate Prediction)	Nuclear	1983	•It is the most popular first-generation technique. •The human error probability values are assessed through expert judgments and field data. •The event tree analysis is used to associate a positive or negative result to each event performed by the operator.
	HCR [18] Human Cognitive reliability	Nuclear	1984	•It uses the Rasmussen subdivision to determine nominal HEP- •It provides a time-reliability curve parametrized for the decision-making type- •Its main disadvantage is that a small variation in the task assessment produces differences in the HEP also up to two orders of magnitude.
	SLIM [19] Success Likelihood Index Method	Nuclear	1984	•It calculates a Success Likelihood Index for each task based on importance weight and scaled rating of different PSFs. •It provides an uncertainty bound analysis and a cost-effectiveness analysis.
	HEART [20] Human Error Assessment and Reduction Technique	General purpose	1985	•The HEP of each task is influenced by one or more EPC (Error Producing Condition). •It provides useful suggestions to reduce the occurrence of errors. •It relies extensively to the expert opinion.
Second Generation	**CREAM** [21] Cognitive Reliability and Error Analysis Method	Mainly for nuclear/ chemical plants	1998	•It has been designed for both predictive and retrospective analysis. •It is based on Contextual Control Model (COCOM) which considers four modes of control, namely Scrambled, Opportunistic, Tactical and Strategic control. •It is clear, structured and systematic but on the other hand it results to be too complex.
	ATHEANA [22] A Technique for Human Error Analysis	Nuclear	1996	•It allows to adopt preventive actions to reduce the occurrence of a human error and to improve the whole level of system safety. •It is a qualitative method. •It is usually performed after an accident.
	SPAR-H [23] Standardized Plant Analysis of Risk-Human Reliability Analysis	Nuclear	2005	•It is based on a three-type classification for the human task, namely: action, diagnosis or both diagnosis and action. •It is one of the few methods which consider that PSFs have both negative and positive influence on the error probability. •It uses eight different Performance Shaping Factors to consider the appropriate context.
Third generation	**NARA** [24] Nuclear Action Reliability Assessment	Nuclear	2005	•It is an improvement of the HEART technique, specifically applied to the nuclear industry. •It contains a new database for the nominal HEP collected by including direct observation, recording, simulator observation, incident data and expert judgement. •It uses the Assessed proportion of affect (APOA) for each EPC.
	PROCOS [25] Probabilistic Cognitive Simulator	General purpose	2007	•It integrates a cognitive human error analysis with HAZOP and event tree. •It is a semi-static approach which considers different contexts changing the PSFs and the parameters about the human performance.
	SAFPHR [26] Systems Analysis for Formal Pharmaceutical Human Reliability	Medical	2020	•It combines concepts from CREAM with probabilistic model checking. •It is based on a computational tool which automatically provides properties about complex, stochastic systems.
	BN-SLIM [27] Bayesian Network SLIM	Nuclear	2020	•It uses Bayesian Network for improving the performances of SLIM in handling uncertainty arising from expert's opinion and lack of data. •It considers uncertainty associated with the PSFs by means of probabilistic assessment.
	Phenix [28] **and Phoenix-PRO** [29]	Nuclear - Petroleum Refining Operations	2016 2020	•It is a qualitative technique which integrates Hybrid Causal Logic model, with Event Sequence Diagrams, Fault Trees and Bayesian Belief Networks. •It has been developed for nuclear applications in 2016 (Phoenix) and then extended to Oil&Gas plant in 2020 (Phoenix-PRO).
	RANDAP [30] Reliability Analysis of Detailed Action Plans	Nuclear	2013	• A Reliability Block Diagram technique is implemented with the aim of modeling the reliability of integrated automatic-operator emergency actions. • It focuses on incorporating operator's operational and cognitive errors in the process/equipment reliability analysis
	SHERPA [31] Simulator for Human Error Probability Analysis	General purpose	2015	•It estimates the human error probability as a Weibull function dependent from the working time. •It provides a dynamic model which allows a flexible evaluation of the human performance. •It includes the performance shaping factors of the SPAR-H technique.

Grozdanovic [33] proposes the use of SLIM technique to analyze the human error probability of an operator working in a railway control center. In [34] the human error during a train monitoring and control system assessment has been studied. Train cab simulators have been used in [35] to collect human error probability data on train driver fault diagnosis. In [36] authors introduce the concept of railway engineering among other industrial fields proposing the Analysis of Consequences of Human Unreliability (ACIH). Some works propose to use HEART technique to estimate HEP in railway-related systems. For instance, in [37] authors use HEART method as part of a risk assessment evaluation of existing yard switching operations and remote-control locomotive operations in the United States. Zhou *et al.* [38] estimates the HEP in locomotive driving processes using a hybrid HEART approach. However, HEART technique has not been specifically developed for railway, and consequently some adaptations are required. Other papers enhance first-generation techniques to estimate the HEP in railway field. For instance, in [39] the SLIM method has been combined with empirical study and network analysis while in [40] SLIM is integrated with Analytic Network Process. More generally, the research interest in HRA in railway field is moving toward the extension of already existing HRA methods initially developed for other fields due to the lack of available data and available techniques specifically developed for railway.

The RSSB developed the RARA (Railway Action Reliability Assessment) model in 2012 [13]. RARA is the most common HRA technique in railway engineering since it is the only one specifically developed only for this kind of applications. It classifies the human activities in railway within eight different Generic Task Types (GTTs) grouped into three categories: more automated and skill-based processes; more effortful and rule-based processes; thinking outside procedures. For each GTT the method provides a range of variation of the human error probability and a nominal value within this range. RARA also considers 27 different Error Producing Conditions (EPCs) to consider the internal and external factors that influence the human behavior. For each one of the EPC the technique provides the Maximum Affect (MA) that the considered EPC will have on the operator. The MA value is weighted by means of the APOA (Assessed proportion of affect) to evaluate how much the EPC actually affects the task, as follow:

$$A = (\mathrm{MA} - 1) \cdot \mathrm{APOA} + 1 \tag{1}$$

$$\mathrm{APOA} \in [0.1, 1] \tag{2}$$

where the greater the APOA, the greater the affect A that the EPC will have on the task. Finally, RARA considers:

- $\mathrm{HEP_{nom}}$ the error probability of the selected GTT;
- $\mathrm{A_i}$ the generic affect of the $\mathrm{EPC_i}$;
- n the number of selected EPC;

Then the RARA model calculates the human error probability HEP as follow:

$$\mathrm{HEP} = \mathrm{HEP_{nom}} \cdot \prod_{i=1}^{n} \mathrm{A_i} \tag{3}$$

$$\mathrm{HEP} = \mathrm{HEP_{nom}} \cdot \prod_{i=1}^{n} [(\mathrm{MA_i} - 1) \cdot \mathrm{APOA_i} + 1] \tag{4}$$

Human Reliability Analysis requires failure data to achieve quantitative analysis. However, it is not always possible to fully obtain this data due to unavailability of observations and consequent scarcity of statistical data about errors and failures [41]. Therefore, some works introduce fuzzy set theory to handle reliability evaluation under conditions of uncertainty. Some papers in literature deal with a fuzzy cognitive reliability and error analysis method - fuzzy CREAM [42], [43]. These methods use fuzzy logic to calculate human error probability applying if-then rules and a defuzzification procedure. The main disadvantages of the fuzzy-based CREAM available in literature [42], [43] are the time-consuming processes required to develop the rules and the risk of using contradicting rules. To solve the problems of too many rules needed and incomplete or contradicting rules some advanced methods like monotone fuzzy rules relabeling, monotone interval fuzzy inference systems, monotone fuzzy rules interpolations, and hierarchical fuzzy inference systems, have been proposed in other field of applications. Regarding HRA, Rotshtein *et al.* [44] proposes a procedure which introduced membership functions of fuzzy perfection of performance conditions and the theory of decision-making in CREAM. To validate the approach five scenarios have been considered. Zhou *et al.* [45] uses the fuzzy logic to model the uncertainty and ambiguity of the Common Performance Conditions (CPCs) as well the control modes in CREAM. The probability distribution of each control mode and consequently the human error probability are evaluated by means of a Bayesian network and the membership functions of the CPCs. Another work [46] develops a fuzzy Bayesian network (BN) approach to improve the quantification of organizational influences in HRA (human reliability analysis) frameworks. Kumar *et al.* [47] presents Fuzzy HEART and expert elicitation to evaluate the HEP of refueling operations in an LPG refueling station. This approach integrates the fuzzy membership functions during the assessment of the Error Producing Conditions. Finally, their new approach has been validated comparing the results obtained with the classical CREAM assessment. Bayesian networks and fuzzy logic have been also used in [48].

III. PROPOSED FUZZY-BASED APPROACH

This section illustrates the proposed fuzzy-based approach used to evaluate the human error probability for railway engineering. Taking the database of the RARA method, the proposed approach consists in several steps in order to calculate the HEP in a simpler way for the analyst ensuring consistent results. Since data regarding human failures are not always available, the proposed approach starts with the already validated data provided by RARA. Then, fuzzy logic is used to combine the base human error probability and the external affect conditions in order to estimate the probability of committing an error during the work shift. Fuzzy ratings have been used as ratings because they help mitigate the drawbacks of ambiguous and uncertain data suffered by classical ratings. Moreover, fuzzy logic allows to minimize the subjectivity of the HEP evaluation by means of linguistic variables instead of crisp number. In fact, the analyst that carry out the evaluation must choose between different Membership Functions (MFs) and their associated linguistic variable instead of picking a value within the range of the HEP or choosing an APOA value to quantify the Affect A_i of each EPC. The steps of the proposed fuzzy approach are illustrated in fig. 1 and are described as follow:

1. **Preliminary GTT fuzzification.**
   - 1.1 Use HEP_{min}, HEP_{max} and HEP_{nom} provided by RARA for each GTT to identify the domain of the fuzzy set.
   - 1.2 Identify 3 to 5 MFs for each fuzzy set of the GTT.
2. **Preliminary EPC fuzzification.**
   - 2.1 Calculate min (APOA = 0.1) and max (APOA = 1) value of any affect considered by RARA.
   - 2.2 Create a domain of the fuzzy set for each affect.
   - 2.3 Define 5 MFs for each affect.
3. **Identification of the proper GTT.**
   - 3.1 Select a Generic Task Type (GTT).
   - 3.2 Select a MF for the considered GTT.
4. **Identification of the EPC.**
   - 4.1 Select any Error Producing Conditions i which are relevant to the task being assessed.
   - 4.2 Select a MF for each EPC.
5. **Calculation of the Human Error Probability $\widetilde{HEP}$.**
6. **Defuzzification of the fuzzy $\widetilde{HEP}$.**

RARA method is based on eight different GTTs. For each one of them RARA provides a minimum value of the error probability HEP_{min}, a maximum value HEP_{max} and a nominal value HEP_{nom} which correspond to the most probable error probability for the considered task [13]. All the considered GTTs and the corresponding minimum, maximum and nominal HEP are included in Table 2.

Step 1 of the proposed procedure uses these values to calculate the fuzzy human error probability associated to each GTT. More in detail, a fuzzy base human error probability $\widetilde{HEP}_{b_i}$ will be associated to each kind of task i as:

$$\widetilde{HEP}_{b_i} = \left\{\left(x, \mu_{GTT_i}(x)\right) | x \in D_{GTT_i}\right\} \tag{5}$$

$$\mu_{GTT_i}(x) : D_{GTT_i} \rightarrow [0, 1] \tag{6}$$

$$D_{GTT_i} = \left[HEP_{min_i}, HEP_{max_i}\right] \tag{7}$$

where $\mu_{GTT_i}(x)$ represents the membership functions of the task i while D_{GTT_i} is the domain of possible admissible value by the fuzzy base error probability $\widetilde{HEP}_{b_i}$ of the GTT i. As in Equation (7) domain D_{GTT_i} is generated using the minimum and maximum values of the HEP provided by RARA for each GTT.

For instance, taking the GTT R4 as an example, the domain of possible admissible values $D_{GTT_{R4}}$ by the fuzzy base error probability $\widetilde{HEP}_{b_{R4}}$ is given by Equation (7) and Table 2 as follow:

$$D_{GTT_i} = [0.2\%, 0.4\%] \tag{8}$$

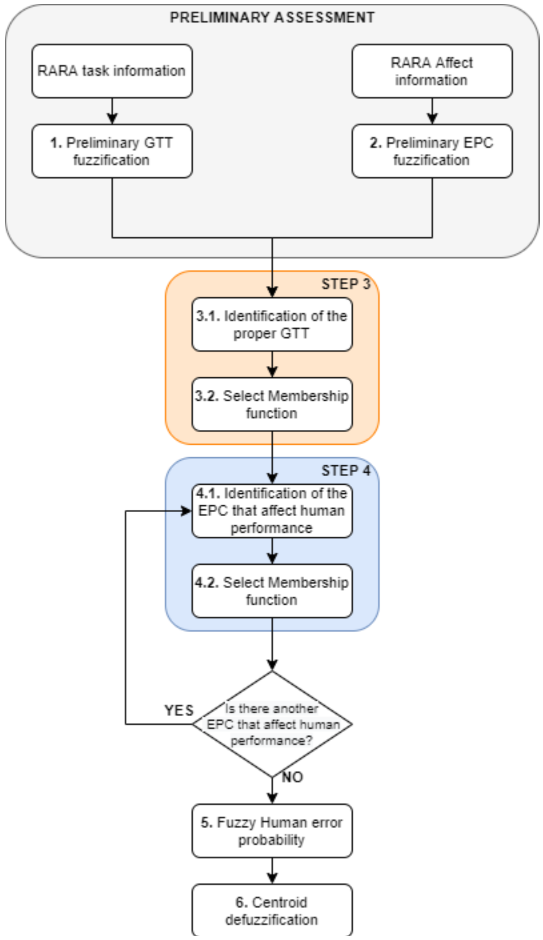

FIGURE 1. Flowchart of the proposed fuzzy-based approach used to estimate the human error probability in railway engineering.

TABLE 2. Generic task type and human error probability according to RARA technique [13].

Generic Task Type	HEP_{min}	HEP_{nom}	HEP_{max}
R1. Respond correctly to system command even when there is an automated system providing accurate interpretation of system state.	0.0006%	0.002%	0.09%
R2. Completely familiar, well designed, highly practiced task which is routine.	0.008%	0.04%	0.7%
R3. Simple response to a dedicated alarm and execution of actions covered in procedures.	0.008%	0.04%	0.7%
R4. Skill-based tasks (manual, visual or communication) when there is some opportunity for confusion.	0.2%	0.3%	0.4%
R5. Fairly simple task performed rapidly or given insufficient or inadequate attention.	6%	9%	13%
R6. Restore or shift a system to original or new state, following procedures with some checking.	0.08%	0.3%	0.7%
R7. Identification of situation requiring interpretation of alarm/ indication patterns.	2%	7%	17%
R8. Complex task requiring a high level of understanding and skill.	12%	16%	28%

Then, according to Equation (6), the membership functions of GTT R4 must follow the following:

$$\mu_{GTT_{R4}}(x) : [0.2\%, 0.4\%] \rightarrow [0, 1] \tag{9}$$

More in detail, the fuzzy set $\widetilde{HEP_{bR4}}$ is composed by 3 MFs within the domain $D_{GTT_{R4}}$. For illustrative purposes only, one of these three MFs is included in Table 3 in compliance with Equation (5) and considering a small sampling rate for the sake of simplicity.

The results of the complete preliminary fuzzification step are shown in fig. 2, where the fuzzy sets developed for each GTT are illustrated. Inside the domain D_{GTT_i} of each task a different number of trapezoidal membership functions (three, four or five) have been defined depending on the extension of the domain itself. Trapezoidal MFs have been used since they are the most common functions in reliability applications according to [41], [49]. A linguistic variable has been assigned to each MF of each GTT in order to intuitively describes the probability of error of the considered GTT.

Six different linguistic variables with increasing probability values have been developed, namely: {Very Low; Low; Moderate; Medium; High; Very High}. Along with minimum and maximum values of HEP for each GTT, RARA also provides a nominal value which according to the original technique is the most probable value within the range. To take into account also this information provided by RARA the membership function that encloses the RARA nominal HEP has been developed larger than the others, with more values with maximum degree of membership.

TABLE 3. Example of membership function assessed for GTT R4 using equations (5)- (7).

x	Degree of membership $\mu_{GTT_{R4}}(x)$
0.2	0
0.22	0
0.24	0.5
0.26	1
0.28	1
0.3	1
0.32	1
0.34	0.5
0.36	0
0.38	0
0.4	0

The second step is quite similar to the first one. The objective of the fuzzification this time is the value of the Affect A of each EPC j. RARA evaluates the Affect of each EPC by means of the Maximum Affect MA and the APOA value as in Equation (1). The proposed method introduces linguistic variables instead of the APOA value to estimate the level of affect with lower subjectivity. More in detail, the fuzzy affect $\widetilde{A}_j$ of each EPC j is defined as follow:

$$\widetilde{A}_j = \left\{ \left(z, \mu_{EPCj}(z)\right) | z \in D_{EPC_j} \right\} \tag{10}$$

$$\mu_{EPCj}(z) : D_{EPC_j} \rightarrow [0, 1] \tag{11}$$

$$D_{EPC_j} = \left[A_{min_j}, A_{max_j}\right] \tag{12}$$

where $\mu_{EPC_j}(x)$ stands for the membership functions of the EPC j while D_{EPC_j} represents the domain of possible admissible value by the fuzzy affect $\widetilde{A}_j$ of the EPC j. The minimum A_{min_j} and maximum A_{max_j} affect values of each EPC j used to generate the domain D_{EPC_j} have been evaluated setting the minimum and maximum APOA values respectively within Equation (1), as follow:

$$A_{min_j} = (MA - 1) \cdot 0.1 + 1 \tag{13}$$

$$A_{max_j} = (MA - 1) \cdot 1 + 1 = MA \tag{14}$$

For instance, according to RARA, the EPC T2: "A shortage of time available for error detection and correction." is characterized by MA = 11. Thus, in compliance with Equations (12)-(14) the domain of the EPC T2 is given by:

$$A_{min_{T2}} = (11 - 1) \cdot 0.1 + 1 = 2 \tag{15}$$

$$A_{max_{T2}} = (11 - 1) \cdot 1 + 1 = 11 = MA \tag{16}$$

$$D_{EPC_{T2}} = [2, 11] \tag{17}$$

Then, after the estimation of the domain of all the EPCs taken into account by RARA, five trapezoidal membership functions have been designed within each domain D_{EPC_j}. Successively, a linguistic variable has been assigned to each MF developed in this work to rapidly and easily describes the affect level of the considered EPC.

The five corresponding linguistic variables are the following {Very Low; Low; Moderate; High; Very High}.

The results of the preliminary EPCs fuzzification step are shown in Table 4, where the fuzzy sets developed for each EPC are listed. For the definition of each EPC see [13].

For the sake of brevity, the following notation for trapezoidal membership function have been used in table 4:

$$A_{TRAP} = (z_1, z_2, z_3, z_1) \tag{18}$$

where the relationship between mathematical notation and trapezoidal membership function is explained in fig. 3.

The two above-described steps are preliminary phases carried out only one time. It is not necessary to repeat the GTT and EPC fuzzification steps every time that a human error probability is assessed by means of the proposed method. Therefore, a suitable tool has been specifically developed using MATLAB R2020b to automatize the assessment using the proposed method. A screenshot of the Graphical User Interface is reported in fig. 4. The top left panel of the developed software allows to select the Generic Task Type that better describes the task that the operator must perform. Then the panel also allows to select the membership function that is the optimal choice (Step 3) according to the analyst performing the assessment. The top figure in the center of the tool illustrates the membership functions of the selected task

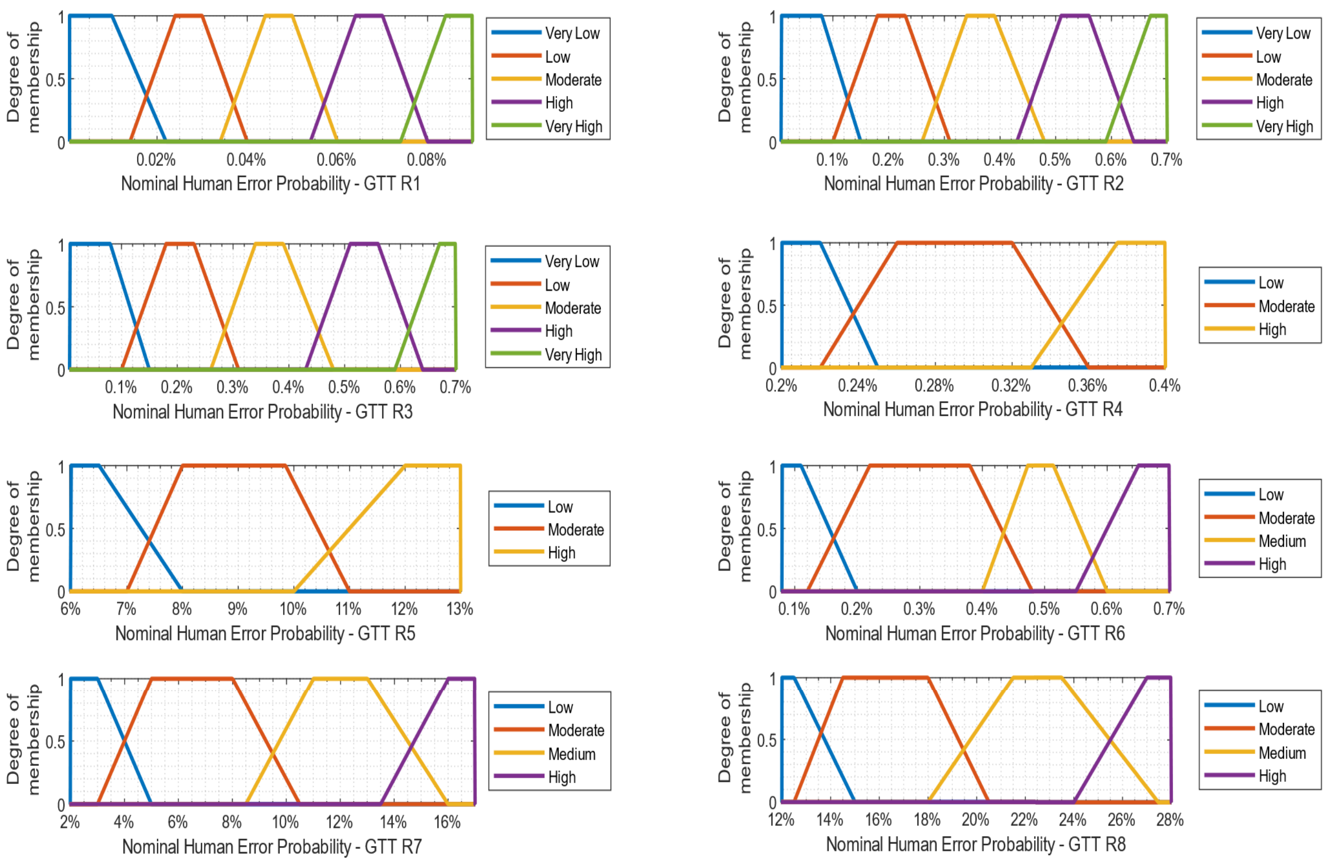

FIGURE 2. **Membership functions proposed to estimate the HEP of each generic task type (GTT) included in the procedure.**

within the proper domain D_{GTT_i}. The bottom left panel of the software allows to select the EPC that affect the performances of the operator. It also allows to select the membership function using the linguistic variable that better describe the affect level of the selected EPC (Step 4). The bottom figure in the center of the tool illustrates the membership functions of the selected task within the proper domain D_{EPC_j}. Step 4 could be repeated several times selecting different EPCs. The right panel in the developed tool resumes the selected task and the selected EPC with their relative membership functions. Fig. 5 shows the data entry dialog box of the developed software after the selection of GTT and all EPCs.

The top subplot in the central panel of the tool illustrates the selected membership function of the proper GTT (in this case task R6, membership function "Low"). The bottom subplot shows the last chosen EPC, while the complete list of EPC is reported in the right panel.

The following step (Step 5) consists in the evaluation of the fuzzy human error probability $\widetilde{HEP}$ by means of fuzzy arithmetic. The choice of fuzzy multiplication in spite of a rule-based methods has been made because of its simplicity and its easiness of implementation. To perform fuzzy arithmetic operations, the α-cut theory has been taken into account. Any fuzzy set can be described by specifying its α-cut. More in detail, a fuzzy set can be obtained as upper envelope of its α-cut, where the α-cut of a fuzzy set X is a crisp set X_α that contains all elements in the domain that have membership degree greater than or equal to α. Considering two fuzzy sets X and Y described using the following trapezoidal membership functions $\mu_X(z)$ and $\mu_Y(z)$ respectively [50], [51]:

$$\mu_X(z) = \begin{cases} \dfrac{z-a_X}{b_X-a_X} & \text{if } a_X < z < b_X \\ 1 & \text{if } b_X \leq z < c_X \\ \dfrac{d_X-z}{d_X-c_X} & \text{if } c_X \leq z < d_X \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

$$\mu_Y(z) = \begin{cases} \dfrac{z-a_Y}{b_Y-a_Y} & \text{if } a_Y < z < b_Y \\ 1 & \text{if } b_Y \leq z < c_Y \\ \dfrac{d_Y-z}{d_Y-c_Y} & \text{if } c_Y < z < d_Y \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

Then the α-cut of the fuzzy sets X and Y are given by [52], [53]:

$$X_\alpha = [X_{\alpha-L}, X_{\alpha-R}] \tag{21}$$

TABLE 4. Trapezoidal membership functions proposed to estimate the effects of each EPC included in the procedure.

Area	Ref	Max Effect	Very Low	Low	Moderate	High	Very High
Task design	T1	17	(2.6, 2.6, 2.96, 5.84)	(2.96, 5.84, 6.56, 9.44)	(6.56, 9.44, 10.16, 13.04)	(10.16, 13.04, 13.76, 16.64)	(13.76, 16.64, 17, 17)
	T2	11	(2, 2, 2.225, 4.025)	(2.225, 4.025, 4.475, 6.275)	(4.475, 6.275, 6.725, 8.525)	(6.725, 8.525, 8.975, 10.78)	(8.975, 10.78, 11, 11)
	T3	8	(1.7, 1.7, 1.857, 3.117)	(1.857, 3.117, 3.432, 4.693)	(3.433, 4.692, 5.007, 6.267)	(5.007, 6.268, 6.582, 7.843)	(6.583, 7.843, 8, 8)
	T4	5.5	(1.45, 1.45, 1.551, 2.361)	(1.551, 2.361, 2.563, 3.374)	(2.564, 3.373, 3.576, 4.386)	(3.576, 4.387, 4.588, 5.399)	(4.589, 5.399, 5.5, 5.5)
	T5	3	(1.2, 1.2, 1.245, 1.605)	(1.245, 1.605, 1.695, 2.055)	(1.695, 2.055, 2.145, 2.505)	(2.145, 2.505, 2.595, 2.955)	(2.595, 2.955, 3, 3)
	T6	3	(1.2, 1.2, 1.245, 1.605)	(1.245, 1.605, 1.695, 2.055)	(1.695, 2.055, 2.145, 2.505)	(2.145, 2.505, 2.595, 2.955)	(2.595, 2.955, 3, 3)
	T7	2.5	(1.15, 1.15, 1.184, 1.454)	(1.184, 1.454, 1.521, 1.791)	(1.521, 1.791, 1.859, 2.129)	(1.859, 2.129, 2.196, 2.466)	(2.196, 2.466, 2.5, 2.5)
	T8	1.6	(1.06, 1.06, 1.074, 1.181)	(1.073, 1.181, 1.209, 1.317)	(1.209, 1.317, 1.344, 1.451)	(1.343, 1.452, 1.479, 1.587)	(1.479, 1.587, 1.6, 1.6)
	T9	1.4	(1.04, 1.04, 1.049, 1.121)	(1.049, 1.121, 1.139, 1.211)	(1.139, 1.211, 1.229, 1.301)	(1.229, 1.301, 1.319, 1.391)	(1.319, 1.391, 1.4, 1.4)
	T10	1.1	(1.005, 1.005, 1.006, 1.015)	(1.006, 1.015, 1.017, 1.026)	(1.017, 1.026, 1.029, 1.038)	(1.029, 1.038, 1.04, 1.049)	(1.04, 1.049, 1.05, 1.05)
Interface	In1	10	(1.9, 1.9, 2.103, 3.722)	(2.102, 3.723, 4.127, 5.748)	(4.127, 5.747, 6.152, 7.772)	(6.152, 7.772, 8.178, 9.798)	(8.178, 9.797, 10, 10)
	In2	9	(1.8, 1.8, 1.98, 3.42)	(1.98, 3.42, 3.78, 5.22)	(3.78, 5.22, 5.58, 7.02)	(5.58, 7.02, 7.38, 8.82)	(7.38, 8.82, 9, 9)
	In3	8	(1.7, 1.7, 1.857, 3.117)	(1.857, 3.117, 3.432, 4.693)	(3.433, 4.692, 5.007, 6.267)	(5.007, 6.268, 6.582, 7.843)	(6.583, 7.843, 8, 8)
	In4	8	(1.7, 1.7, 1.857, 3.117)	(1.857, 3.117, 3.432, 4.693)	(3.433, 4.692, 5.007, 6.267)	(5.007, 6.268, 6.582, 7.843)	(6.583, 7.843, 8, 8)
	In5	8	(1.7, 1.7, 1.857, 3.117)	(1.857, 3.117, 3.432, 4.693)	(3.433, 4.692, 5.007, 6.267)	(5.007, 6.268, 6.582, 7.843)	(6.583, 7.843, 8, 8)
	In6	6	(1.5, 1.5, 1.613, 2.513)	(1.612, 2.513, 2.737, 3.638)	(2.737, 3.638, 3.862, 4.763)	(3.862, 4.763, 4.987, 5.888)	(4.987, 5.888, 6, 6)
	In7	4	(1.3, 1.3, 1.367, 1.908)	(1.368, 1.908, 2.042, 2.583)	(2.043, 2.583, 2.718, 3.258)	(2.718, 3.258, 3.393, 3.933)	(3.393, 3.933, 4, 4)
Competence Management	C	9	(1.2, 1.2, 1.245, 1.605)	(1.245, 1.605, 1.695, 2.055)	(1.695, 2.055, 2.145, 2.505)	(2.145, 2.505, 2.595, 2.955)	(2.595, 2.955, 3, 3)
Procedures	PR1	5	(1.4, 1.4, 1.49, 2.21)	(1.49, 2.21, 2.39, 3.11)	(2.39, 3.11, 3.29, 4.01)	(3.29, 4.01, 4.19, 4.91)	(4.19, 4.91, 5, 5)
	PR2	3	(1.2, 1.2, 1.245, 1.605)	(1.245, 1.605, 1.695, 2.055)	(1.695, 2.055, 2.145, 2.505)	(2.145, 2.505, 2.595, 2.955)	(2.595, 2.955, 3, 3)
Person	P1	4	(1.3, 1.3, 1.367, 1.908)	(1.368, 1.908, 2.042, 2.583)	(2.043, 2.583, 2.718, 3.258)	(2.718, 3.258, 3.393, 3.933)	(3.393, 3.933, 4, 4)
	P2	2.6	(1.16, 1.16, 1.196, 1.484)	(1.196, 1.484, 1.556, 1.844)	(1.556, 1.844, 1.916, 2.204)	(1.916, 2.204, 2.276, 2.564)	(2.276, 2.564, 2.6, 2.6)
	P3	2	(1.1, 1.1, 1.123, 1.303)	(1.123, 1.303, 1.348, 1.528)	(1.347, 1.528, 1.573, 1.753)	(1.572, 1.752, 1.797, 1.978)	(1.797, 1.978, 2, 2)
	P4	1.8	(1.08, 1.08, 1.098, 1.242)	(1.098, 1.242, 1.278, 1.422)	(1.278, 1.422, 1.458, 1.602)	(1.458, 1.602, 1.638, 1.782)	(1.638, 1.782, 1.8, 1.8)
	P5	1.4	(1.04, 1.04, 1.049, 1.121)	(1.049, 1.121, 1.139, 1.211)	(1.139, 1.211, 1.229, 1.301)	(1.229, 1.301, 1.319, 1.391)	(1.319, 1.391, 1.4, 1.4)
	P6	1.2	(1.02, 1.02, 1.024, 1.06)	(1.024, 1.06, 1.069, 1.105)	(1.069, 1.105, 1.114, 1.15)	(1.115, 1.151, 1.159, 1.196)	(1.159, 1.196, 1.2, 1.2)
Environment	E	8	(1.7, 1.7, 1.857, 3.117)	(1.857, 3.117, 3.432, 4.693)	(3.433, 4.692, 5.007, 6.267)	(5.007, 6.268, 6.582, 7.843)	(6.583, 7.843, 8, 8)

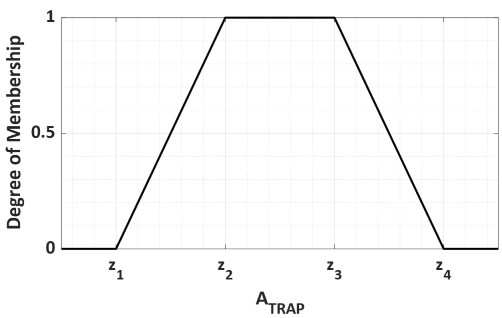

FIGURE 3. Example of a generic trapezoidal membership function.

$$X_\alpha = \left[a_X + \alpha^{1/n}(b_X - a_X),\, d_X - \alpha^{1/n}(d_X - c_X)\right] \quad (22)$$

$$Y_\alpha = [Y_{\alpha-L}, Y_{\alpha-R}] \quad (23)$$

$$Y_\alpha = \left[a_Y + \alpha^{1/n}(b_Y - a_Y),\, d_Y - \alpha^{1/n}(d_Y - c_Y)\right] \quad (24)$$

The multiplication of two fuzzy sets could be achieved using interval arithmetic, as follow [54]–[56]:

$$T_\alpha = X_\alpha \odot Y_\alpha = [T_{\alpha-L}, T_{\alpha\text{-}R}] \quad (25)$$

$$T_{\alpha-L} = \min(X_{\alpha-L} \cdot Y_{\alpha-L}, X_{\alpha-L} \cdot Y_{\alpha-R}, X_{\alpha\text{-}R} \cdot Y_{\alpha-L}, X_{\alpha\text{-}R} \cdot Y_{\alpha\text{-}R}) \quad (26)$$

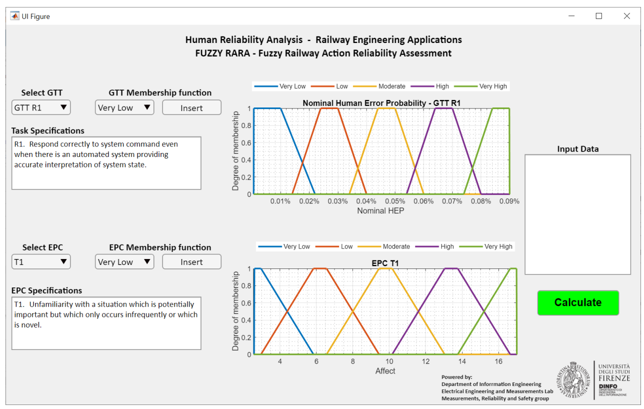

FIGURE 4. MATLAB graphical user interface developed to rapidly implement the proposed approach for HEP estimation. The screenshot represents the dialog box for data entry.

$$T_{\alpha\text{-}R} = \max(X_{\alpha-L} \cdot Y_{\alpha-L}, X_{\alpha-L} \cdot Y_{\alpha\text{-}R}, X_{\alpha\text{-}R} \cdot Y_{\alpha-L}, X_{\alpha\text{-}R} \cdot Y_{\alpha\text{-}R}) \quad (27)$$

where the operator $\odot$ is the multiplication between two fuzzy sets performed by means of α-cut and interval arithmetic.

Finally, according to [52] the membership function $\mu_T(z)$ of the fuzzy set $T_\alpha = [T_{\alpha-L}, T_{\alpha\text{-}R}]$ achieved after

FIGURE 5. Screenshot of the MATLAB tool after the selection of GTT and EPC. The input data are collected inside the right panel. The figure illustrates the selected task and the last chosen EPC.

multiplication of two fuzzy sets is given by:

$$\mu_T(z) = \begin{cases} f_1(z) & \text{if } a_X a_Y < z < b_X b_Y \\ 1 & \text{if } b_X b_Y \leq z \leq c_X c_Y \\ f_2(z) & \text{if } c_X c_Y < z < d_X d_Y \\ 0 & \text{otherwise} \end{cases} \quad (28)$$

The functions $f_1(z)$ and $f_2(z)$ are not linear relationships as in Equation (19) or Equation (20). Instead, the effect of the multiplication by α-cut is the alteration of the trapezoid shape into semi-trapezoid shape where the linear increase and decrease from $\mu_T = 0$ to $\mu_T = 1$ and vice versa become a square root function.

The above-mentioned theory of fuzzy multiplication has been used to evaluate the fuzzy human error probability $\widetilde{HEP}$ (Step 5). In particular, the latter is given by the product of the fuzzy membership function of the selected task $\widetilde{HEP_{b_i}}$ (selected during Step 3) with an overall weighting factor $\widetilde{W}$. Thus, the fuzzy human error probability is given by:

$$\widetilde{HEP} = \widetilde{HEP_b} \odot \widetilde{W} \quad (29)$$

The weighting factor $\widetilde{W}$ is a fuzzy set which takes into account every affect $\widetilde{A_j}$ selected during Step 4. The following equation is used to obtain this factor:

$$\widetilde{W} = \widetilde{A_1} \odot \widetilde{A_2} \odot \cdots \odot \widetilde{A_p} = \prod_{j=1}^{p} \widetilde{A_j} \quad (30)$$

where p is the number of selected EPC during the several repetition of Step 4. The product symbol $\prod$ in Equation (30) represents the fuzzy product $\odot$ of a sequence of factors. Consequently, substituting Equation (30) into Equation (29) the fuzzy $\widetilde{HEP}$ is given by:

$$\widetilde{HEP} = \widetilde{HEP_b} \odot \prod_{j=1}^{p} \widetilde{A_j} \quad (31)$$

where $\widetilde{HEP}$ is the fuzzy human error probability described by the membership function $\mu_{HEP}(z)$.

Finally, Step 6 consists in the defuzzification of the obtained fuzzy human error probability using the centroid method.

Starting from a fuzzy number and its corresponding membership function the defuzzification procedure is the process of generating a crisp logic value related to the starting fuzzy value. The centroid defuzzification is one of the most implemented defuzzification method in reliability engineering according to [41]. It returns HEP* which is the center of gravity of the fuzzy number described by the membership function $\mu_{HEP}(z)$ as follow [57]:

$$HEP^* = \frac{\int z \cdot \mu_{HEP}(z)\, dz}{\int \mu_{HEP}(z)\, dz} \quad (32)$$

The developed tool automatically implements Step 5 and Step 6 after the selection of the base HEP and the affect value of the proper EPCs. The output box of the developed tool is illustrated in Fig. 6, where both fuzzy human error probability $\widetilde{HEP}$ and defuzzified HEP* are shown.

The developed software allows an easy and rapid implementation of the proposed fuzzy-based approach. The analyst is able to perform the HEP assessment following just few simple steps without have to deal with numerical estimations. The linguistic variables used in the tool allows to easily carry out the assessment in a way that is more suitable to human reasoning, decreasing subjectivity and possibility of error during the evaluation.

Furthermore, this procedure allows to easily simulate different scenarios for the considered task easily and rapidly changing the membership functions of the selected EPCs or simply introducing or removing one or more EPCs.

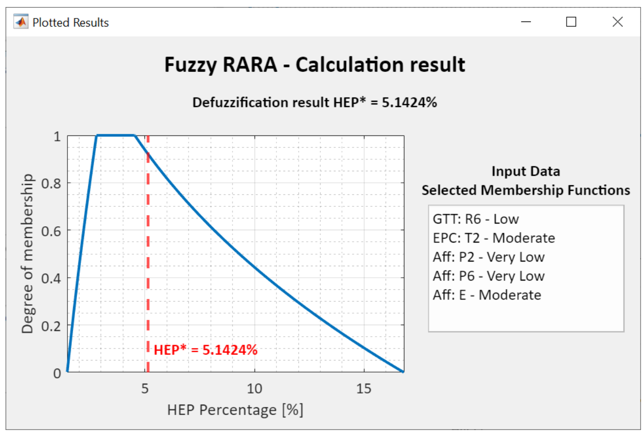

FIGURE 6. Output box of the developed MATALB graphical user interface. The software provides the fuzzy HEP and the defuzzification result, along with a note with the selected membership functions used to evaluate the HEP.

IV. CASE STUDY

A. AUTOMATIC TRAIN PROTECTION SYSTEM

Railway signaling systems are used to regulate the safe movements of trains. This kind of systems are able to direct railway traffic in order to keep trains clear of each other at any times. In order to do that, railway signaling systems comprise train detection units used to identify the exact position of each train, semaphores, different kind of signals, a centralized traffic unit and several safety-related systems used to protect the safety of passengers and operators in case of failure (including hardware failure, software malfunctions and human errors).

One of the most important safety-oriented systems is the Automatic Train Protection (ATP). It is used to constantly monitor the speed of the train in order to ensure that the current speed is compatible with the speed allowed by signaling in the area of interest. In case the train speed overcomes the allowed track speed, then the ATP detects this hazardous condition and it activate an emergency brake to decrease the train speed or, in particular circumstances, to stop the train. Therefore, ATPs are particularly useful to identify both hardware failures and/or human errors. If the driver of the train fails to obey an instruction of railway signaling the ATP mitigates this failure adapting the train speed to the requirement of the signaling [58], [59]. ATPs are based on two subunits interacting with each other:

- An onboard subsystem.
- A ground subsystem.

The ground unit of the ATP under test is illustrated in Fig. 7. It comprises a set of two antennas (usually called balises) deployed in different points of the rail tracks. Usually, these kinds of transponder are located near a semaphore or a reduced speed zone and they are used to relay information regarding the signaling to the onboard subsystem of the passing train. Most of the available ATPs use two nearby balises located in the center of the railroad track to ensure high reliability and safety requirements.

To avoid crosstalk and ensure a correct communication between onboard unit and ground unit a set of strict requirements are forced during the balise installation.

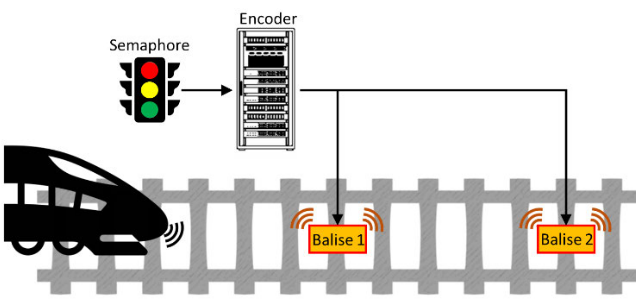

FIGURE 7. Scheme of the automatic train protection system under test highlighting the devices of the ground subunit (two balises, an encoder and a semaphoric unit).

Another important equipment of the ATP under analysis included within the ground subsystem is the encoder which is used to convert the signaling information from semaphores and signals into messages suitable for the balises.

B. HUMAN ACTIVITIES PERFOMED ON ATP

An Automatic Train Protection system is a reliable and safe equipment used to correct the train driver errors. Therefore, it is improbable that a driver error will lead to an accident if ATP are properly used. Consequently, the human activities significant for the safety of the railway systems mainly reside in the design, installation, verification and maintenance phases of the ATP itself. Table 5 includes the most critical human activities performed by specialized operator on the ATP under analysis. These activities have been studied in the next subsections in order to estimate the human error probability of each operation in different scenarios.

TABLE 5. Human operations performed on the ground unit of an automatic train protection system.

Operation	Description
Balise Laying	It requires several operations: track ballast removal, positioning and fixing of the support, laying of the connection cable, and finally laying of the balise. Strict design requirements are required in term of tolerance of the installation angle and positioning of connection cable. A nearby metal-free zone is required.
Balise configuration	It is performed connecting the balise to a computer through a connection cable.
Maintenance	It requires several operations: fault detection, fault isolation, configuration of a new balise, replacement of the failed balise. Several measuring instruments are generally used.
Encoder wiring	It requires the correct connection of the cables to the encoder. It is a critical task since incorrect connection could lead to the transmission of incorrect information to the train.

C. HUMAN ERROR PROBABILITY ESTIMATION

After the preliminary steps 1-2 automatically performed by the developed tool, step 3 of the proposed procedure consists in the selection of the proper task for the considered human operation. The four above-described human operations have been studied considering:

- Balise Laying: GTT R3 has been chosen since this is a simple task performed following suitable well-defined procedures. The selected MF is the lowest admissible (''Very Low'') since it is a standardized procedure carried out by well-trained operator.
- Balise Configuration: GTT R4 has been selected because this is a skill-based task performed by a well-trained operator. The operation is simple, but there is some possibility of confusion due to the programming of several identical balises. The selected MF is the lowest admissible (''Low'').
- Maintenance: GTT R6 is the task of RARA specifically developed for maintenance actions following a procedure. The selected MF is the lowest admissible (''Low'')

since it is a standardized procedure carried out by experienced operator.

- Encoder wiring: GTT R3 has been selected since this is a simple action performed following suitable well-defined procedures. The selected MF is "Low" which is a bit higher than the balise laying since it requires a higher mental involvement.

Once selected the GTT and its membership function, some scenarios of the external and internal conditions are proposed. In particular, for each one of the operation two different scenarios are taken into account:

1. Optimal case is the most likely situation.
2. Stressed and Fatigued when the operators are tired and stressed because of previous work or personal reasons.

Both scenarios consider the same EPCs as follow:

- T2: "a shortage of time available for error detection and correction". To perform the operations on ATP, the railway line must have been blocked. Thus, the operators have to work quickly to minimize the railroad unavailability.
- P2: "fatigue from shift and work patterns". It represents the likelihood that operators are tired from the previous works.
- P6: "low workforce morale". It stands for the consequences of the fatigue and stress from the work shift.
- E: "a poor or hostile environment". These operations have to be performed outdoor on the track and generally at night, moreover sometimes the work locations are accessible only by walking.

Some important EPCs which are usually taken into account during this kind of analysis has been neglected thanks to fundamental information provided by the company that manage operation and maintenance of the ATP under analysis. In particular, EPCs related to experience of the operators and their perceived risk have been neglected since the operators that perform the tasks are experienced and well-trained regarding the risk of their work. Moreover, detailed documentations regarding the specific tasks is regularly provided by the company to the operator allowing the analyst to neglect several others EPCs.

Table 6 summarizes all the scenarios considered in this work. For the sake of representation, only the first letter of each linguistic variable has been used, namely VL = Very Low, L = Low, M = Moderate, H = High and VH = Very High.

The four tasks have been studied considering the above-mentioned EPCs and taking into account both stressed and non-stressed operators (Scenario 1. And 2. Respectively). The EPCs P2 and P6 related to stress and fatigue conditions have been set "Very Low" for all the tasks in the Optimal scenario, while have been set "Very High" for all the tasks in the second scenario. This option allows to easily quantify the effect of a stressed and fatigued operator on the human error probability. The environment-related EPC (E) has been set "Moderate" in case the operation has to be performed on the tracks (i.e. Balise laying and Maintenance), while it has a minor effect ("Very Low") in case the task is performed near the tracks (i.e. Balise configuration and Encoder wiring). Finally, the T2 EPC related to the available time has been set considering the average task duration of each task.

TABLE 6. Input data used to calculate the human error probability of the four considered operations in two different scenarios.

Operation	Selected Task	Scenario	EPC			
			T2	P2	P6	E
Balise laying	GTT R3 "Very Low"	1. Optimal Case	M	VL	VL	M
		2. Stressed and Fatigued	M	VH	VH	M
Balise configuration	GTT R4 "Low"	1. Optimal Case	VL	VL	VL	L
		2. Stressed and Fatigued	VL	VH	VH	L
Maintenance	GTT R6 "Low"	1. Optimal Case	M	VL	VL	M
		2. Stressed and Fatigued	M	VH	VH	M
Encoder wiring	GTT R3 "Low"	1. Optimal Case	L	VL	VL	L
		2. Stressed and Fatigued	L	VH	VH	L

The results of the Human Error Probability assessment (Step 5 and Step 6) are illustrated in Fig. 8. Each subplot shows fuzzy human error probability $\widetilde{HEP}$ (continuous trend) and defuzzified HEP* (vertical dotted line) of a single task in both the considered scenarios. The Optimal case is illustrated using blue lines, while the red color stands for the Stressed and Fatigued scenario.

Analyzing Fig. 8 is clear that the P2 and P6 EPCs related to the stress and fatigue conditions of the operator deeply affect the human performances. Both fuzzy $\widetilde{HEP}$ and defuzzified value HEP* show a remarkable increase when the second scenario is taken into account. Such increment remarks the importance of stress management to ensure a low error probability.

Furthermore, railway companies should develop the working shift and the maintenance operations taking into account the negative effect of fatigue and long consecutive shifts.

In addition, is fundamental to note that the defuzzification operation is a practical but also a simple solution for ordering of outcomes. Defuzzification allows to remove all the uncertainties providing a single crisp value which represents the complete fuzzy set. Despite the removal of the complete fuzzy set, the defuzzified crisp value can still provide satisfactory ordering outcomes as it is possible to see in Fig. 8. The major contribution of the defuzzified outcome is given by the easiness of results comparison and outcomes ordering. However, one of the potentialities of the proposed fuzzy-based method is the results contained in the complete fuzzy set domain (including uncertainties). Therefore, analysts should always take into account both the complete fuzzy

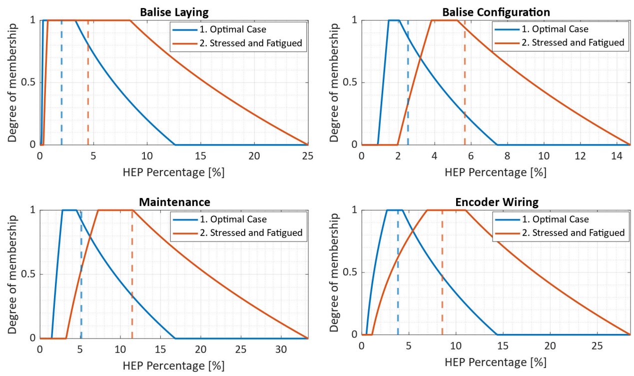

FIGURE 8. Results of the proposed approach. Fuzzy human error probability and defuzzified HEP considering two different scenarios (optimal case in blue and stressed and fatigued in red). Each plot illustrates the results of a different activity.

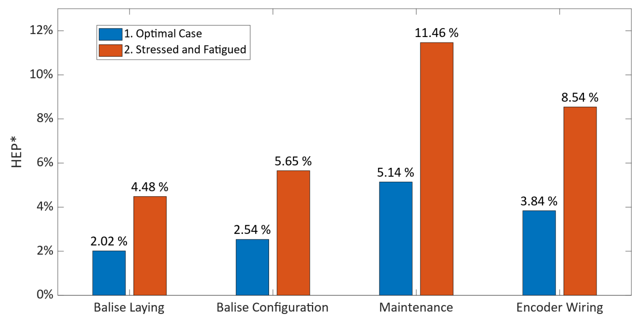

FIGURE 9. Bar chart of the defuzzified HEP* obtained using the proposed approach considering four different tasks and two simulation scenarios (1. Optimal case using blue and 2. Stressed and Fatigued using red).

set and the defuzzified outcome because each output provides useful information.

In order to better compare the results of the proposed approach, Fig. 9 illustrates a bar chart of the defuzzified HEP*. Each set of bars stands for a different operation. The optimal case is illustrated using blue bars, while the red bars stand for the Stressed and Fatigued scenario. What stands out from the figure is that the Maintenance Operation is the most challenging task for the ATP under analysis in both the analyzed scenarios. This is mainly due to the fact that the maintenance operation requires a sequence of different activities involving fault diagnosis, control and verification. Another critical task is the encoder wiring which provides the second highest HEP* due to the high number of cables to be connected. Balise laying and balise configuration result to be less critical and challenging, with a lower human error probability.

The proper working of railway signaling systems is fundamental to ensure safety of passengers and operator. Therefore, the latter comparison should be useful to companies to take adequate countermeasures and prevent a high likelihood of accident due to human errors. First of all, railway companies should plan the working shifts trying to avoid fatigued and stressed operator.

Even if the operator could be stressed and fatigued not only because of previous work shifts, it is essential to guarantee adequate rest to the workers in order to minimize the probability of a human error during maintenance, installation and verification phases of ATP. Furthermore, the ordering outcome of the four studied tasks must be carefully considered by companies during the work planning. Since maintenance has proven to be a much more complex tasks characterized by higher error probability, it is important to ensure that only highly specialized and well-trained experienced operator will perform such critical task.

V. COMPARISON WITH AN EXISTING METHOD

In order to test and validate the effectiveness of the fuzzy-based proposed approach the results of the previous analysis are compared with a human error probability estimation achieved using the well-known RARA method.

The RARA technique has been chosen as state-of-the-art comparison because it represents the only HRA method specifically developed for railway engineering. Furthermore, RARA is the starting point of the proposed fuzzy-based approach. Consequently, a comparison with RARA is mandatory to validate the results achieved by the proposed method. At the same time, it also represents the only comparative analysis significant for the scope of this work.

Table 7 summarizes the input data required by the RARA method for each one of the considered tasks. For the sake of comparison, the GTT and the EPCs selected in the RARA assessment are the same one used in the proposed approach. The nominal HEP of each task has been selected within the range of the admissible value provided by RARA following the guidelines of the company that manage operation and maintenance of the ATP under analysis. The APOA value of each EPC has been assessed following the same considerations of the previous analysis. Each Affect is calculated using Equation (1), while the resulting HEP is evaluated with Equation (3).

The comparison between RARA and the proposed fuzzy-based approach is shown in Table 8, where the HEP of the four operations is reported considering both scenarios.

The differences between the Human Error Probability provided by RARA and proposed approach are negligible leading to comparable results of all the studied operations. Therefore, the proposed approach is validated by the comparison with the widest used technique in railway engineering.

The main advantages of the proposed fuzzy-based method are the following:

- The proposed approach provides a range of possible HEP with different degree of membership. This is a fundamental skill since HRA is not an exact science and therefore is not recommended to consider a crisp HEP value.
- Fuzzy logic is the most suitable approach in case of incomplete and uncertain data. In fact, data regarding

human error in railway are not always available, especially in case of near miss.

- Comparing the required input data for the proposed approach and the RARA method is extremely evident how the parameters assessment is easier using the proposed approach. In fact, the use of linguistic variables to assess the input data is closer to human intuition than numbers assessment.
- Fuzzy minimizes subjectivity of the assessment as well as it accurately balances the tradeoff between precision and significance.

TABLE 7. Input data used to calculate the human error probability using the RARA method available in literature.

Operation	Scenario	Parameters	EPC			
			T2	**P2**	**P6**	**E**
Balise laying GTT R3 HEP_{nom}=0.05%	1. Optimal Case	MA	11	2.6	1.2	8
		APOA	0.6	0.1	0.1	0.6
		Affect	7	1.16	1.02	5.2
	2. Stressed and Fatigued	MA	11	2.6	1.2	8
		APOA	0.6	0.9	0.9	0.6
		Affect	7	2.44	1.18	5.2
Balise configuration GTT R4 HEP_{nom}=0.2%	1. Optimal Case	MA	11	2.6	1.2	8
		APOA	0.2	0.1	0.1	0.3
		Affect	3	1.16	1.02	3.1
	2. Stressed and Fatigued	MA	11	2.6	1.2	8
		APOA	0.2	0.9	0.9	0.3
		Affect	3	2.44	1.18	3.1
Maintenance GTT R6 HEP_{nom}=0.11%	1. Optimal Case	MA	11	2.6	1.2	8
		APOA	0.6	0.1	0.1	0.6
		Affect	7	1.16	1.02	5.2
	2. Stressed and Fatigued	MA	11	2.6	1.2	8
		APOA	0.5	0.9	0.9	0.6
		Affect	7	2.44	1.18	5.2
Encoder wiring GTT R3 HEP_{nom}=0.1%	1. Optimal Case	MA	11	2.6	1.2	8
		APOA	0.4	0.1	0.1	0.4
		Affect	5	1.16	1.02	3.8
	2. Stressed and Fatigued	MA	11	2.6	1.2	8
		APOA	0.4	0.9	0.9	0.4
		Affect	5	2.44	1.18	3.8

TABLE 8. State-of-the-art comparison between classical RARA method and proposed fuzzy-based approach.

Operation	1. Optimal Case		2. Stressed and Fatigued	
	Proposed approach	RARA	**Proposed approach**	RARA
Balise Laying	**2.0153%**	2.1534%	**4.4833%**	5.2401%
Balise Configuration	**2.5365%**	2.2008%	**5.6543%**	5.3553%
Maintenance	**5.1424%**	4.7375%	**11.4646%**	11.5283%
Encoder Wiring	**3.8386%**	2.2481%	**8.5443%**	5.4705%

VI. CONCLUSION

Human errors are one of the primary causes of accidents in railway. Despite several different techniques are available to study human reliability, Railway Action Reliability Assessment (RARA) is the only method specifically developed for railway industry. In this paper an innovative fuzzy-based approach has been presented to evaluate the human error probability of railway-related operations. The database of RARA has been used as a starting point for the proposed procedure. Then, fuzzy logic has been implemented to overcome the subjectivity of the assessment and to deal with the uncertain data that characterize human reliability analysis. The α-cut theory and fuzzy interval arithmetic are used to calculate the human error probability.

To test and validate the performances of the proposed approach, the procedure has been applied to four human operations performed on an automatic train protection system. The method shows full compatibility of the results provided by RARA, without necessity to select number and values during the assessment. Therefore, this procedure could be performed also by non-expert analysts with minimum subjectivity.

REFERENCES

[1] M. Catelani, L. Ciani, G. Guidi, and G. Patrizi, ''An enhanced SHERPA (E-SHERPA) method for human reliability analysis in railway engineering,'' *Rel. Eng. Syst. Saf.*, vol. 215, Nov. 2021, Art. no. 107866.

[2] J. Liu, F. Schmid, W. Zheng, and J. Zhu, ''Understanding railway operational accidents using network theory,'' *Rel. Eng. Syst. Saf.*, vol. 189, pp. 218–231, Sep. 2019.

[3] F. De Felice and A. Petrillo, *Human Factors and Reliability Engineering for Safety and Security in Critical Infrastructures: Decision Making, Theory, and Practice*. Cham, Switzerland: Springer-Verlag, 2018.

[4] S. Qiu, M. Sallak, W. Schön, and Z. Cherfi-Boulanger, ''Evaluation of human error probabilities based on classical HRA models: An application to railway systems,'' in *Proc. Qualita*, Nancy, France, Mar. 2015, pp. 1–9.

[5] *UIC Safety Report 2020. Significant Accident 2019 Public Report*, UIC Saf.f Unit, Paris, France, 2020.

[6] *Railway Applications—The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS)—Part 1: Basic Requirements and Generic Process*, Standard EN 50126, CENELEC, European Committee for Electrotechnical Standardization, 2017.

[7] R. L. Boring, *Advances in Human Error, Reliability, Resilience, and Performance*, vol. 589. Cham, Switzerland: Springer, 2018.

[8] L.-X. Hou, R. Liu, H.-C. Liu, and S. Jiang, ''Two decades on human reliability analysis: A bibliometric analysis and literature review,'' *Ann. Nucl. Energy*, vol. 151, Feb. 2021, Art. no. 107969.

[9] E. Zarei, F. Khan, and R. Abbassi, ''Importance of human reliability in process operation: A critical analysis,'' *Rel. Eng. Syst. Saf.*, vol. 211, Jul. 2021, Art. no. 107607.

[10] L. Ciani, D. Galar, and G. Patrizi, ''Improving context awareness reliability estimation for a wind turbine using an RBD model,'' in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (I2MTC)*, May 2019, pp. 1–6.

[11] M. Catelani, L. Ciani, D. Galar, and G. Patrizi, ''Optimizing maintenance policies for a yaw system using reliability-centered maintenance and data-driven condition monitoring,'' *IEEE Trans. Instrum. Meas.*, vol. 69, no. 9, pp. 6241–6249, Sep. 2020.

[12] *Guidance on Human Aspects of Dependability*, Standard IEC62508, International Electrotechnical Commision, 2010.

[13] H. Gibson, ''Railway action reliability assessment user manual—A technique for the quantification of human error in the rail industry,'' Rail Saf. Standards Board, London, U.K., Tech. Rep. T270 Manual, 2012, pp. 1–96.

[14] J. Park, W. Jung, and J. Kim, ''Inter-relationships between performance shaping factors for human reliability analysis of nuclear power plants,'' *Nucl. Eng. Technol.*, vol. 52, no. 1, pp. 87–100, Jan. 2020.

[15] P. Liu, Y. Qiu, J. Hu, J. Tong, J. Zhao, and Z. Li, "Expert judgments for performance shaping Factors' multiplier design in human reliability analysis," *Rel. Eng. Syst. Saf.*, vol. 194, Feb. 2020, Art. no. 106343.

[16] E. Hollnagel, "Looking for errors of omission and commission or the hunting of the snark revisited," *Rel. Eng. Syst. Saf.*, vol. 68, no. 2, pp. 135–145, May 2000.

[17] D. Swain and H. E. Guttmann, *Handbook of Reliability Analysis With Emphasis on Nuclear Plant Applications*. Albuquerque, NM, USA: Sandia National Laboratories, Aug. 1983, doi: 10.2172/5752058.

[18] G. Hannaman, A. Spurgin, and Y. Lukic, "Human cognitive reliability model for PRA analysis," Electr. Power Res. Inst., Palo Alto, CA, USA, Draft Rep. NUS-4531, EPRI Project Rep. RP2170-3, 1984.

[19] D. E. Embrey, P. Humphreys, E. A. Rosa, B. Kirwan, and K. Rea, "SLIM-MAUD: An approach to assessing human error probabilities using structured expert judgment. Volume I. Overview of SLIM-MAUD," Brookhaven Nat. Lab., Upton, NY, USA, Tech. Rep. NUREG/CR-3518, 1984.

[20] J. C. Williams, "HEART—A proposed method for achieving high reliability in process operation by means of human factors engineering technology," in *Proc. Symp. Achievement Rel. Oper. Plant, Saf. Rel. Soc.*, 1985, pp. 5-1–5-15.

[21] E. Hollnagel, *Cognitive Reliability and Error Analysis Method*, 1st ed. Amsterdam, The Netherlands: Elsevier, 1998.

[22] S. E. Cooper, "A technique for human error analysis (ATHEANA): Technical basis and methodology description," US Nuclear Regulatory Commission, Washington, DC, USA, Tech. Rep. NUREG/CR-6350, BNL-NUREG-52467, 1996.

[23] D. Gertman, H. Blackman, J. Marble, J. Byers, and C. Smith, "The SPAR-H human reliability analysis method," U.S. Nucl. Reg. Commission, Rockville, MD, USA, Tech. Rep. NUREG/CR-6883, 2005.

[24] B. Kirwan, H. Gibson, R. Kennedy, J. Edmunds, G. Cooksley, and I. Umbers, "Nuclear action reliability assessment (NARA): A data-based HRA tool," *Saf. Rel.*, vol. 25, no. 2, pp. 38–45, Jun. 2005.

[25] P. Trucco and M. C. Leva, "A probabilistic cognitive simulator for HRA studies (PROCOS)," *Rel. Eng. Syst. Saf.*, vol. 92, no. 8, pp. 1117–1130, Aug. 2007.

[26] X. Zheng, M. L. Bolton, C. Daly, and E. Biltekoff, "The development of a next-generation human reliability analysis: Systems analysis for formal pharmaceutical human reliability (SAFPH)," *Rel. Eng. Syst. Saf.*, vol. 202, Oct. 2020, Art. no. 106927.

[27] S. Abrishami, N. Khakzad, S. M. Hosseini, and P. van Gelder, "BN-SLIM: A Bayesian network methodology for human reliability assessment based on success likelihood index method (SLIM)," *Rel. Eng. Syst. Saf.*, vol. 193, Jan. 2020, Art. no. 106647.

[28] N. J. Ekanem, A. Mosleh, and S.-H. Shen, "Phoenix—A model-based human reliability analysis methodology: Qualitative analysis procedure," *Rel. Eng. Syst. Saf.*, vol. 145, pp. 301–315, Jan. 2016.

[29] M. A. Ramos, E. L. Droguett, A. Mosleh, and M. D. C. Moura, "A human reliability analysis methodology for oil refineries and petrochemical plants operation: Phoenix-PRO qualitative framework," *Reliab. Eng. Syst. Saf.*, vol. 193, Jan. 2020, Art. no. 106672.

[30] N. Vaez and F. Nourai, "RANDAP: An integrated framework for reliability analysis of detailed action plans of combined automatic-operator emergency response taking into account control room operator errors," *J. Loss Prevention Process Ind.*, vol. 26, no. 6, pp. 1366–1379, Nov. 2013.

[31] V. Di Pasquale, S. Miranda, R. Iannone, and S. Riemma, "A simulator for human error probability analysis (SHERPA)," *Rel. Eng. Syst. Saf.*, vol. 139, pp. 17–32, Jul. 2015.

[32] W. H. Gibson, E. D. Megaw, M. S. Young, and E. Lowe, "A taxonomy of human communication errors and application to railway track maintenance," *Cogn., Technol. Work*, vol. 8, no. 1, pp. 57–66, Jan. 2006.

[33] M. Grozdanovic, "Usage of human reliability quantification methods," *Int. J. Occupat. Saf. Ergonom.*, vol. 11, no. 2, pp. 153–159, Jan. 2005.

[34] J. Wreathall, D. Bley, E. Roth, J. Multer, and T. Raslear, "Using an integrated process of data and modeling in HRA," *Rel. Eng. Syst. Saf.*, vol. 83, no. 2, pp. 221–228, Feb. 2004.

[35] W. H. Gibson, M. W. Halliday, L. Sutton, J. Shelton, and M. Bond, "A train driving simulator experiment to investigate driver fault diagnosis," in *People and Rail Systems: Human Factors at the Heart of the Railway*, J. R. Wilson, B. Norris, T. Clarke, and A. Mills, Eds. Boca Raton, FL, USA: CRC Press, 2007.

[36] F. Vanderhaegen, "A non-probabilistic prospective and retrospective human reliability analysis method—Application to railway system," *Rel. Eng. Syst. Saf.*, vol. 71, no. 1, pp. 1–13, Jan. 2001.

[37] S. Reinach and A. Viale, "Application of a human error framework to conduct train accident/incident investigations," *Accident Anal. Prevention*, vol. 38, no. 2, pp. 396–406, Mar. 2006.

[38] J.-L. Zhou, Y. Lei, and Y. Chen, "A hybrid HEART method to estimate human error probabilities in locomotive driving process," *Rel. Eng. Syst. Saf.*, vol. 188, pp. 80–89, Aug. 2019.

[39] J.-L. Zhou and Y. Lei, "A slim integrated with empirical study and network analysis for human error assessment in the railway driving process," *Rel. Eng. Syst. Saf.*, vol. 204, Dec. 2020, Art. no. 107148.

[40] M. Kyriakidis, A. Majumdar, and W. Y. Ochieng, "The human performance railway operational index—A novel approach to assess human performance for railway operations," *Rel. Eng. Syst. Saf.*, vol. 170, pp. 226–243, Feb. 2018.

[41] S. Kabir and Y. Papadopoulos, "A review of applications of fuzzy sets to safety and reliability engineering," *Int. J. Approx. Reasoning*, vol. 100, pp. 29–55, Sep. 2018.

[42] M. Konstandinidou, Z. Nivolianitou, C. Kiranoudis, and N. Markatos, "A fuzzy modeling application of CREAM methodology for human reliability analysis," *Rel. Eng. Syst. Saf.*, vol. 91, no. 6, pp. 706–716, Jun. 2006.

[43] M. Marseguerra, E. Zio, and M. Librizzi, "Human reliability analysis by fuzzy 'CREAM,'" *Risk Anal.*, vol. 27, no. 1, pp. 137–154, Feb. 2007.

[44] A. Rotshtein, L. Pustylnik, and B. A. Polin, "Method of fuzzy perfectness in human reliability analysis: Selection of performance conditions," in *Advances in System Reliability Engineering*. Amsterdam, The Netherlands: Elsevier, 2019, pp. 209–226.

[45] Q. Zhou, Y. D. Wong, H. S. Loh, and K. F. Yuen, "A fuzzy and Bayesian network CREAM model for human reliability analysis—The case of tanker shipping," *Saf. Sci.*, vol. 105, pp. 149–157, Jun. 2018.

[46] P.-C. Li, G.-H. Chen, L.-C. Dai, and L. Zhang, "A fuzzy Bayesian network approach to improve the quantification of organizational influences in HRA frameworks," *Saf. Sci.*, vol. 50, no. 7, pp. 1569–1583, Aug. 2012.

[47] A. M. Kumar, S. Rajakarunakaran, and V. A. Prabhu, "Application of fuzzy HEART and expert elicitation for quantifying human error probabilities in LPG refuelling station," *J. Loss Prevention Process Ind.*, vol. 48, pp. 186–198, Jul. 2017.

[48] P. Baraldi, L. Podofillini, L. Mkrtchyan, E. Zio, and V. N. Dang, "Comparing the treatment of uncertainty in Bayesian networks and fuzzy expert systems used for a human reliability analysis application," *Rel. Eng. Syst. Saf.*, vol. 138, pp. 176–193, Jun. 2015.

[49] K.-Y. Cai, *Introduction to Fuzzy Reliability*. Norwell, MA, USA: Kluwer, 1996.

[50] G. J. Klir and B. Yuan, *Fuzzy Sets and Fuzzy Logic: Theory and Applications*. Upper Saddle River, NJ, USA: Prentice-Hall, 1995.

[51] C. Bector and S. Chandra, "Fuzzy numbers and fuzzy arithmetic," in *Fuzzy Mathematical Programming and Fuzzy Matrix Games*. Berlin, Germany: Springer-Verlag, 2005, pp. 39–56.

[52] S. Rezvani and M. Molani, "Representation of trapezoidal fuzzy numbers with shape function," *Ann. Fuzzy Math. Informat.*, vol. 8, no. 1, pp. 89–112, 2014.

[53] R. Hassanzadeh, I. Mahdavi, N. M. Amiri, and A. Tajdin, "An α-cut approach for fuzzy product and its use in computing solutions of fully fuzzy linear systems," *Int. J. Math. Oper. Res.*, vol. 12, no. 2, p. 167, 2018.

[54] E. Siahlooei and S. A. S. Fazeli, "An application of interval arithmetic for solving fully fuzzy linear systems with trapezoidal fuzzy numbers," *Adv. Fuzzy Syst.*, vol. 2018, pp. 1–10, Jul. 2018.

[55] T. Akther and S. U. Ahmad, "A computational method for fuzzy arithmetic operations," *Daffodil Int. Univ. J. Sci. Technol.*, vol. 4, no. 1, pp. 18–22, Jan. 1970.

[56] W. A. Lodwick and E. A. Untiedt, "A comparison of interval analysis using constraint interval arithmetic and fuzzy interval analysis using gradual numbers," in *Proc. Annu. Meeting North Amer. Fuzzy Inf. Process. Soc. (NAFIPS)*, May 2008, pp. 1–6.

[57] T. J. Ross, *Fuzzy Logic With Engineering Applications*, 3rd ed. Hoboken, NJ, USA: Wiley, 2010.

[58] I. Watanabe and T. Takashige, "Advanced automatic train protection system," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Jun. 1994, pp. 1126–1129.

[59] *Railway Applications—Communication, Signalling and Processing Systems—Safety Related Electronic Systems for Signalling*, Standard EN 50129, CENELEC, European Committee for Electrotechnical Standardization, 2018.

LORENZO CIANI (Senior Member, IEEE) received the M.S. degree in electronic engineering and the Ph.D. degree in industrial and reliability engineering from the University of Florence, Florence, Italy, in 2005 and 2009, respectively. He is currently an Assistant Professor with the Department of Information Engineering, University of Florence. He has authored or coauthored more than 160 peer-reviewed journal articles and conference papers. His current research interests include system reliability, availability, maintainability and safety, reliability evaluation test and analysis for electronic systems and devices, fault detection and diagnosis, and electrical and electronic instrumentation and measurement. He is a member of the IEEE IMS TC-32 Fault Tolerant Measurement Systems. He received the 2015 IEEE I&M Outstanding Young Engineer Award for his contribution to the advancement of instrumentation and measurement in the field of reliability analysis. He is an Associate Editor of IEEE Access and the IEEE Transactions on Instrumentation and Measurement.

GIULIA GUIDI (Student Member, IEEE) received the B.S. degree in electronic and telecommunications engineering and the M.S. degree in electronics engineering from the University of Florence, Florence, Italy, in 2015 and 2018, respectively, where she is currently pursuing the Ph.D. degree in industrial and reliability engineering. Her research interests include the fields of reliability analysis, and optimization of availability and maintainability for railway application.

GABRIELE PATRIZI (Student Member, IEEE) received the B.S. degree in electronic and telecommunications engineering and the M.S. degree in electronics engineering from the University of Florence, Florence, Italy, in 2015 and 2018, respectively, where he is currently pursuing the Ph.D. degree in industrial and reliability engineering. His research interests include in the fields of reliability, availability, maintainability and safety (RAMS) models and experimental analysis for complex systems used in industrial applications.

DIEGO GALAR has been a Visiting Professor with the Polytechnic Institute of Braganza, Portugal, the University of Valencia and NIU, USA, and the Universidad Pontificia Católica de Chile, in the international arena. He is currently a Professor of condition monitoring with the Division of Operation and Maintenance Engineering, Luleå University of Technology (LTU), where he is coordinating several H2020 projects related to different aspects of cyber-physical systems, industry 4.0, and the IoT or industrial big data. He is also a Visiting Professor with the University of Sunderland, U.K., the University of Maryland, USA, the University of Stavanger, Norway, and Chongqing University, China. He is the Principal Researcher in Tecnalia, Spain, heading the Maintenance and Reliability Research Group within the Division of Industry and Transport. He was also involved in the SKF UTC Centre, Lulea, focused on SMART bearings and also actively involved in national projects with the Swedish industry or funded by Swedish national agencies, like Vinnova. He has been involved in the raw materials business of Scandinavia, especially with mining and oil & gas for Sweden and Norway respectively. Indeed, LKAB, Boliden or STATOIL have been partners or funders of projects in the CBM field for specific equipment, like loaders, dumpers, rotating equipment, and linear assets. He has authored more than 500 journal articles and conference papers, books and technical reports in the field of maintenance, and chairing international journals and conferences and actively participating in national and international committees for standardization and research and development in the topics of reliability and maintenance, and also working as a member of editorial boards and scientific committees.