NEW APPROACH OF ASSESSING HUMAN ERRORS IN RAILWAYS

Habib HADJ-MABROUK[1]

Research article

Abstract:	Inspired in particular by the works of Reason and Rasmussen and supported by application examples from the field of railway safety, the human error analysis approach proposed to improve the level of safety of rail transport systems involves three complementary levels. The first level of contextual analysis (before the accident) makes it possible to study the various factors favoring the production of the human error at the origin of the accident. The second cognitive level (during the accident) aims to identify the errors related to the human cognitive process involved in a given situation of insecurity. The third level of behavioral analysis (after the accident) focuses on evaluating the consequences of a wrong action in terms of damage to humans, the environment and the human-machine system. This article proposes an original methodological framework for the analysis, classification and evaluation of human errors involved in the safety of rail transport. The key factors taken into account in the analysis concern not only the inappropriate behavior of human operators involved in railway safety and risk management, but also the technical failures of the transport system and the operating and environmental conditions.
Keywords:	Rail safety; Human error; Feedback of experience; Incident investigation; Human error classification.

Introduction

The adverse consequences and the considerable cost of accidents due to the human factor, the occurrence of new disasters despite the progress of technology, are at the basis of the establishment of a system of feedback of experience (REX) as being the an essential means of promoting the necessary improvement of safety. The main objective of this system is to learn from an experience lived to avoid its reproduction. With the improvement of the technical reliability, the current trend is to attribute the malfunctions of the systems, generators of accidents, to an error of the human operator. The operator is considered as weak point of the system and limiter of performance and safety. Thus, human error constitutes a major causal factor for the emergence of accidents in several safety sectors, including rail transport. The REX consists of analyzing the circumstances leading to the occurrence of unintended adverse events. It is a dynamic process of collecting, storing, analyzing and using data related to unhealthy situations. Its objective is to benefit from the lessons learned to improve the level of safety by implementing

the appropriate preventive and corrective measures in order to avoid the reproduction of such a risk-bearing situation. Other work focuses on the Rex as a decision support process. It allows providing the right knowledge at the right time and at the right level so that the operator responsible for safety can make the right decision. Its purpose is to provide actors with the knowledge they need to make decisions. The REX consists, then, in the management of the knowledge coming from a positive and / or negative event making it possible to take the appropriate decisions in situations of the same nature in the future. Some authors consider that REX is a learning process. In the face of a risky situation, the REX, as a process of acquiring knowledge and learning, not only allows to identify knowledge, but also to share it among the actors concerned. This is an approach that aims to highlight the shortcomings, dysfunctions and incompatibilities of the safety system and to formulate proposals that can avoid such situations or reduce the consequences. It is a detailed study and an in-depth analysis of significant accidents or incidents for a better knowledge of their generating mechanisms. The REX is essential for detecting unpredictable events, especially during

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[1] French institute of science and technology of transport, spatial planning, development and networks, Marne la Vallée, France, habib.hadj-mabrouk@ifsttar.fr

the design and commissioning of the system. The aim is twofold, it's not just about learning lessons for effective, short-term safety-related remedies, but also to capitalize and evolve the deep knowledge of human and material behaviors in the medium term. Broadly speaking, the purpose of the REX is to manage information from an event, including the collection and storage of data, the processing and analysis of such data, the actual use of the results obtained and their transmission to share information experience. Nevertheless, the current the REX system faces several obstacles and limitations, the most important of which are problems related to the analysis of human factors. It is generally deficient and remains limited to a technical dimension. Even if the methods currently available are satisfactory and have been proven to analyze and exploit technological incidents, this is not the case for incidents involving human failure. The REX is much less efficient and much more limited when it concerns the human factor aspect and operational events directly or indirectly involving human intervention. For a deeper analysis of the REX, the reader can refer to the following works: (Joing and Keravel, 1993; Wibaux, 1995; Quatre, 1999; Amalberti and Barriquault, 1999; Gilbert, 2001; Hadj-Mabrouk, 2003, 2016). In the rail transport sector, safety is a key concern for transport system operators and for national, European and international authorities. Whatever the mode of transport (land, sea or air), the transport sector is an activity that constantly involves serious risks on the one hand because of the speed related to the movement of vehicles, and on the other hand, for public transport which generates internal risks for travelers and external risks for third parties, residents living near infrastructures and for the environment. However, the importance of human factors aspects in achieving safety objectives is unanimously accepted by all actors (infrastructure manager, railway undertaking, national safety authority, technical survey bodies, European Agency for safety of the railroads) during the phases of design, realization, validation, homologation, certification, authorization of start-up, maintenance and feedback of experience (Rex) after accidents or incidents. Beyond this recognition in principle, it is clear that taking into account these human factors is still perfectible. They are not formally and systematically integrated into the practices of industrialists in the railway sector. Whether in the industrial field or in the transport sector, the human factors approaches implemented is not very experienced, or even rarely understood. One of the difficulties lies in the multitude of ways of understanding the human factors aspects in particular the definition of the methods and

the work tasks entrusted to the human operator, the precise determination of the limits of the latter, the design of interfaces adequate men-machines and the mastery of new knowledge relating to the human and social sciences (ergonomics, psychology, sociology ...). Various disciplines have addressed the issue, giving rise to multiple concepts, models, and methods (De-keyser, 1982; Norman, 1983; Swain and Guttmann, 1983; Leplat, 1989; Cellier, 1990; Fadier, 1994; Salminen and Tallberg, 1996; Amalberti, 2001). Despite the undeniable interest of these approaches, their implementation in the field of rail transport safety, and in particular in the feedback of experience (Rex) process, remains difficult and sometimes impossible. In order to provide an element of answer, this article proposes an approach of integration of the human factors in the Rex process making it possible to appreciably improve the level of safety of the rail transport systems. This contribution is organized around three levels of hierarchical analysis:

- The first level of "contextual" analysis (before the accident) makes it possible to study the various factors favoring the production of the human error at the origin of the accident;
- The second "cognitive" level (during the accident) aims to identify errors related to the human cognitive process involved in a given situation of insecurity;
- The third level of behavioral analysis (after the accident) focuses on assessing the consequences of a bad action in terms of damage to humans, the environment and the human-machine system.

Regulatory context of the study

The work presented in this paper is part of the scientific policy of our Institute IFSTTAR (French institute of science and technology of transport) and especially in our initial research problematic, that is to say the analysis and the evaluation of the safety of rail transport, and in its indispensable extension to the consideration of human factors in the field of safety. The lack of links between these two disciplines and their complementarities has been deplored many times, including by our guardianships. Taking into account the impact of human factors is also recommended by Directive (EU) 2016/798 of the European parliament and of the council of 11 may 2016 on railway safety (Directive / EU 2016): *"The Safety Management System (SMS) should, through its processes, help to ensure that human capabilities and limitations, as well as influences on human performance, are taken into account through the application of factor knowledge humans and*

the use of recognized methods". Indeed, according to this new European directive n° 2016/798, and in the case where the direct cause of an accident or an incident seems linked to human actions, *"it is necessary to pay attention to the particular circumstances of the manner in which normal operations are carried out by staff in the normal course of operation, including the design of the Human-Machine Interface, the appropriateness of the procedures, the conflict of objectives, the workload, as well as all the other circumstances that influenced the event, including physical stress and stress related to work, fatigue or psychological fitness"*.

Human error

The notion of human error is a very broad concept because it has multiple dimensions. Currently, there is no "common repository" to define human error. Indeed, the term human error covers several meanings depending on the angle at which it is analyzed. This diversity of points of view is linked to the multiplicity of disciplines that analyze it (psychology, ergonomics, engineering, sociology, philosophy, law). Generally, the various definitions of human error adopted by researchers and specialists in the field fall into three categories: (a) that which emphasizes the manifestations of errors (industrial approach), b) the one that is based on their modes of production (psycho-cognitive approach) and (c) the one that combines the two principles (psychodynamic approach to work). Human error is thus analyzed according to its negative aspect in terms of the consequences on man, on the system and its environment, or on its positive aspect by examining the mechanisms that explain its production. However, in almost all industrial sectors at risk and in particular in rail transport, human error has long been identified as the first factor contributing to the occurrence of rail accidents and incidents. Indeed, statistics show that human error is responsible for 70 to 90% of incidents and human operators were then designated as the cause of these accidents or incidents. However, instead of blaming the human operator who is often faced with an increasingly complex system and ignoring the latent conditions of these systems, human error must now be understood as the result of poor human reliability that depends on several performance factors and in particular organizational, professional and individual factors that all interact to influence human reliability. Human error is often only the impossibility in which an operator has to deal with an abnormal situation, be it the failure of a device or an unexpected set of circumstances:

organizational, procedural, environmental change or even alteration of inter-individual relationships. Inherent in all human intervention, human error is a symptom of poor work organization, inadequate or inadequate training. By understanding it and managing it, it can become paradoxically a safety element. Our research work is part of this problematic and seeks to provide elements of answers to this vast problem of taking human factors into account in the feedback of experience with a view to improving risk management methods consequently the safety of rail transport.

The Human Factors Analysis and Classification System: HFACS

The Human Factors Analysis and Classification System (HFACS) provide a methodological framework for analyzing and classifying human errors involved in accidents and incidents. Based on James Reason's "Swiss Cheese" human error model (Reason, 1990), the HFACS system is structured around four levels of hierarchical analysis of active failures and latent (Wiegmann and Shappell, 2003):

1. Unsafe acts: Skill-Based Errors (e.g., a lack of attention), Decision Errors (e.g. inappropriate procedure, rule-based error), Perceptual Errors (e.g. when a decision is made based on erroneous information), Routine Violations and Exceptional Violations;

2. Preconditions for unsafe acts: Physical Environment (e.g. heat, vibration, lighting), Technological Environment (e.g. poor design of equipment and controls, human-machine interfaces), Adverse Mental State (for example, stress, mental fatigue, motivation), Adverse Physiological State (e.g. illness, physical fatigue, hypo vigilance), Physical / Mental Limitation (e.g. visual limitations, insufficient reaction time), Crew Resource Management (e.g. communication, coordination) and Personal Readiness (e.g. alcohol consumption or pharmaceuticals);

3. Hazardous supervision: Inadequate Supervision, Plan Inappropriate Operation, Fail to Correct Known Problem and Supervisory Violation (for example, improper application of procedures and regulations);

4. Organizational or cultural influences: Resource Management, Organizational Climate and Operational Process.

At each level of this organizational hierarchy of human failure, the HFACS approach makes it possible to analyze and identify the different types and categories of human error (i.e. a total of

19 categories of causality). Initially designed for military aviation accident investigations and analysis, the HFACS system has proven to be effective in identifying and analyzing human errors in several areas such as civil aviation, traffic maritime, medical services, coal mines and the railway sector. In the field of rail transport safety, we can mention the work of (Wiegmann and Shappell, 2006; Reinach and Viale, 2006; SanKim and ChulYoon, 2013; Ergai et al. 2016; Madigan et al., 2016; Zhan et al., 2017; Fu,G. et al., 2017; Punzet et al., 2018; Zhou and Lei, 2018). Our study can be part of the HFACS system, but with several improvements and extensions needed to more accurately account for human factors in the feedback of experience after an accident or a rail incident.

Materials and methods

Contextual analysis

It should be recalled that the main objective of the study is to systematically take human factors into account in railway safety studies in accordance with Directive (EU) 2016/798 of the European Parliament and the Council of Europe may 2016 on railway safety. To achieve this objective and consequently to reduce the incidence of rail accidents and incidents, we have examined the various factors favoring the production of human error and in particular the human operator, his working environment, the transport system as well as the various interactions of the human operator with the system and the environment (internal and external). In order to demonstrate the feasibility and the validity of this new approach, we have used some real examples from the field of railway safety and in particular the TGV-Nord high-speed system, the driverless metro type ALV (Automatic Light Vehicle), the Maggaly system from Lyon and the Transmanche Fixed Link system. This study therefore requires the study of the three main components of a socio-technical system (Man, System, and Environment) as well as their interactions. As a first step, we have identified the different types of human operators involved in the safety of rail transport. We focused the study solely on two human operators most involved in the management of rail accident risks: the operator of the centralized command post (CCP) and the train driver. The potential errors of the driving operator are generally divided into two major classes: non-compliance with the signaling (crossing of the stop signal, non-compliance with the lights) and the error of control or maneuvering (e.g. untimely braking). Potential operator errors

in the CCP are often related to failure the berthing procedures, initialization, evacuation or driving procedures. Secondly, we identify the main factors that affect human performance and consequently, directly or indirectly influence the cognitive process of the operator during his activity. Several factors have been identified as physical, physiological, psychological, social, chronobiological, behavioral, professional, chronobiological and factors related to psychosocial risks. These factors can be grouped into three broad categories: 1) Individual factors that include personality, experience, competence, mood, mental and psychological ability, physical ability, and individual health factors such as fatigue, alertness, attention, stress, drugs and alcohol, 2) Work factors that include the physical work environment, working conditions, conflicts of professional or personal values, autonomy and room for maneuver, the human-machine interface, the ergonomics of the workstation , the workload, the availability and quality of information and procedures, the equipment used, the requirements of the task and 3) Organizational factors include organizational priorities, corporate culture, availability of resources, communication systems, social relations, workplace relationships, leadership behavior, performance indicators and economic insecurity such as the change of an uncontrolled task, the conflict or the risk of losing one's job. These individual, professional and organizational factors are closely linked and interact together to influence human reliability. After having identified all the factors related to the Man (individual factors, work factors and organizational factors), it is then necessary to search, for each equipment of the system, the list of the potential human errors. The result of this study allows the designer to take into account, from the first development phase of the system (specification and design), all the potential human errors relating to each category of equipment that are likely to compromise the overall safety of the system. The goal is to integrate, right from the specification and design phases of the system, the appropriate measures to catch, tolerate, reduce or eliminate certain human errors. After analyzing the different human factors related to humans and the system, it is also necessary to identify the various environmental factors likely to influence the good progress of the human activity and in particular the execution of the prescribed task. Identifying these environmental factors, from the design phase of the system, makes it possible to design and implement appropriate preventive ergonomic measures. Finally, during this first phase of contextual analysis of human error, it is essential to identify the various interaction factors between humans, the system and

the internal and external environment of work. For example, the analysis of the interactions between the operator and the system allows the ergonomist designer to take into consideration the problems related to the characteristics of the work (load, position, schedules), to those of the prescribed task (number, duration, time, strength, knowledge ...) and those of the Human Machine Interface.

Cognitive analysis

Taking into account the first contextual analysis mentioned above, the cognitive analysis of human error consists in studying the cognitive mechanisms involved in the production of the error at the origin of the accident. As part of this study, and in order to tend towards the completeness of the analysis, we have agreed to classify human errors along two complementary lines of investigation. In accordance with the work of Reason (Reason, 1990) by Rasmussen (Rasmussen, 1980, 1982, 1986, 1987, 1990) and Rousse (Rouse, 1983), human errors can be classified in two different and complementary ways: 1) either by referring to the three hierarchical levels of human activity (skill-based, rule-based or knowledge-based) or 2) in the different stages of information processing human reasoning or decision-making.

Application: approach of integration of the human error in the feedback of experience

The method we propose (Fig. 1) is inspired by the work of Reason (Reason, 1990), which evokes three levels of classification of human errors (behavioral, contextual and conceptual) corresponding to three questions that one can ask about human errors (what? Where? How?). It is also inspired by Rasmussen's (Rasmussen and Jensen, 1974; Rasmussen, 1980), work on the cognitive functioning of man and Van Eslande (Van-Eslande, 2000) relating to typical accident scenarios. Focusing on the development of a potential accident and supported by some examples from the field of railway safety, this method is based on three complementary levels of analysis of human error and uses the three levels suggested by Reason: contextual level (upstream of the accident), the cognitive conceptual level (during the accident), and the behavioral level (downstream of the accident). In practice, the analysis of the accident first requires a comprehensive study of the environment and the work situation of human operators (upstream of the accident) and thus answers questions where? when? and who? (Type of operator involved).

The second stage of analysis consists of studying the cognitive process implemented in a given situation and thus answers the question how? (During the accident). This approach often leads to action in terms of accomplishing a task. The last phase (downstream of the accident) studies the consequences of a wrong action in terms of damage to man, the environment and the system and thus answers the question what? Thus, through the first two stages of the proposed approach, one can identify the different types of potential human errors as well as their possible interactions. It is for this reason that the proposed approach will focus solely on the first two phases of analysis to determine the various factors involved in producing the potential human errors at the origin of the accident. The objective is to take into account all of these factors in the data collection phase after an accident or railway incident (feedback of experience: Rex).
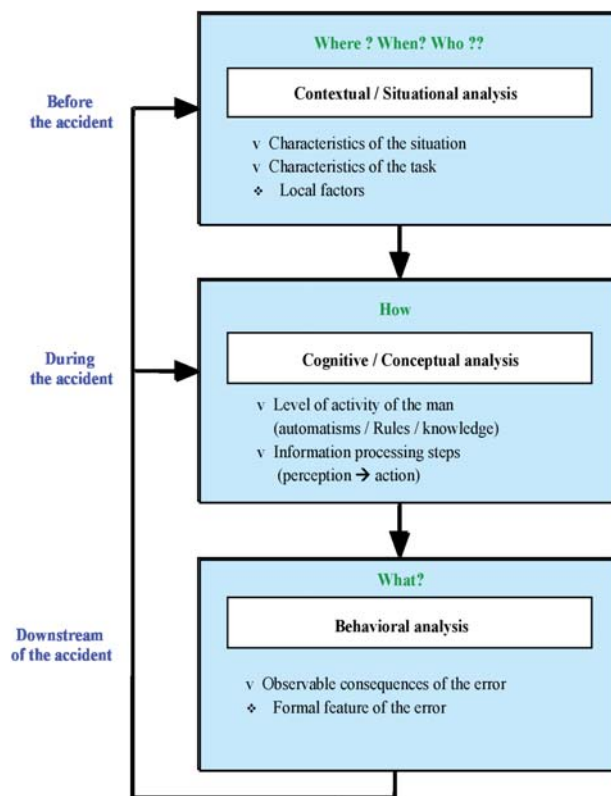

Fig. 1. Articulation of the main levels involved in the analysis of human error in the accident

Before the accident (Contextual analysis)

The contextual analysis of human error, prior to the accident, consists in studying the different working conditions (characteristics of the situation, characteristics of the task ...) favoring its production. Considering the human operator in his work
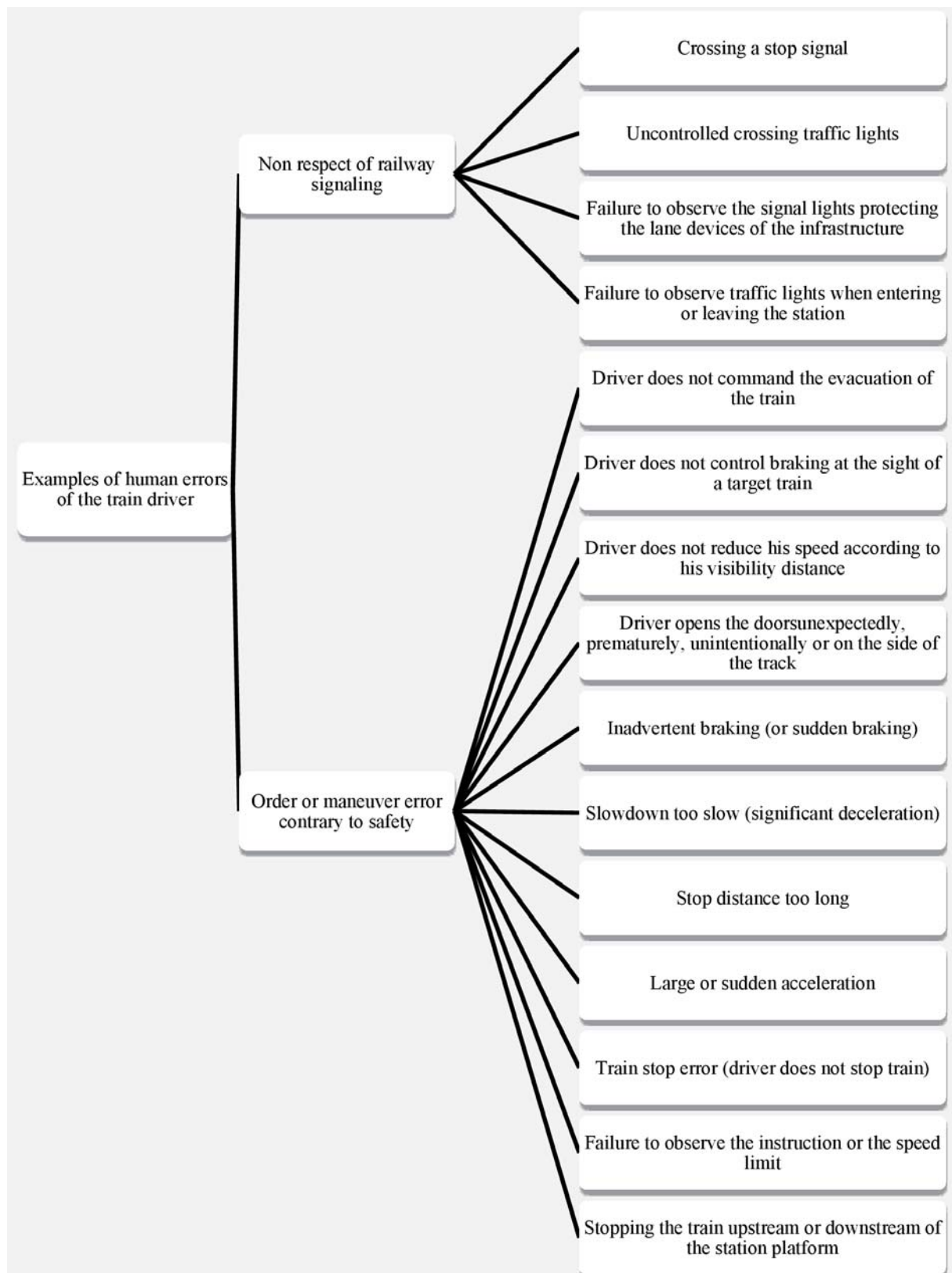
Fig. 2. Example of classification of potential errors caused by the train driver
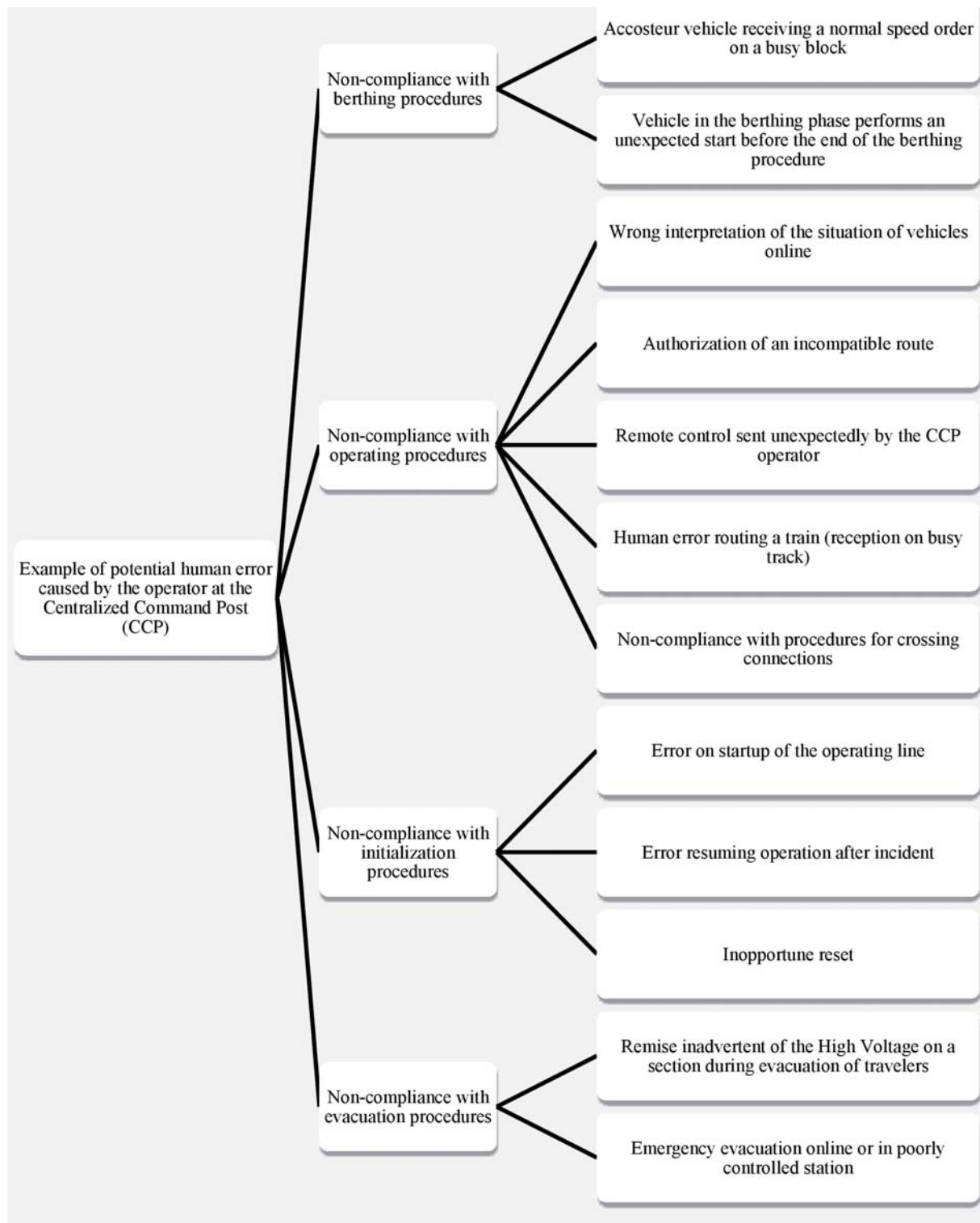
Fig. 3. Example of classification of potential errors caused by the operator at the CCP

environment and in front of the system, this first level of analysis makes it possible to determine the local factors triggering the error as well as the interactions between the internal and external circumstances. The purpose of this phase is to identify the different interactions that the man undergoes with his work

environment, with the other operators and with the system. This level of analysis therefore requires the study of the three main components of a socio-technical system (Man, System, and Environment) as well as their interactions.

a. The Human operator

At first, it is a question of identifying the different types of operators involved as well as the factors that alter human performance. Human operators involved in the transport sector vary depending on the area. In the railway field, for example, the actors are mainly maintenance personnel and operating personnel. Human operating errors include the operator at Centralized Command Post (CCP) and the driver. Potential operator errors in the CCP are often related to failure the berthing procedures, initialization, evacuation or driving procedures. The potential errors of the driving operator are generally divided into two major classes: non-compliance with the signaling (crossing of the stop signal, non-compliance with the lights) and the error of control or maneuvering (untimely braking) or abrupt, non-compliance with the speed instruction, premature or untimely opening of the doors, etc.). Fig. 2 and 3 provide two examples of classification of potential human errors caused respectively by the driving operator (train driver) and the CCP operator.

Tab. 1 Main factors affecting human performance

Physical factors	
Sensory disabilities	Motor disability
Vision	Traumatic brain injury
Hearing	Neurological conditions
Illusion	
Physiological factors	
Health	
Nutrition	
Sleep	
Tired	
Psychological factors	
Personality: panic, stress	
Mood	
Emotional state	
Behavioral factors	
Lifestyle: night activities	
Habits: alcohol, drugs, etc.	
Boredom - distraction	
Apprehension - trust	
Panic - stress	
Professional factors	
Training	
Knowledge	
Experience	

Sociological factors
Family issues
Bad social environment
Visitor, inspector, instructor
Team structure
Chronobiological factors
Circadian typology of sleep: morning / evening
Better performance times: morning / evening
Factors of decline of vigilance
Rhythmic fluctuations of vigilance (circadian, ultradian)
Sleep disorders (sleep deprivation, sleep fragmentation, desynchronization)
Sleep pathologies (Narcolepsy, Sleep Apnea Syndrome)
Ingestion of alcohol
Psychotropic drugs (antidepressants, anxiolytics, etc.)
Factors related to psychosocial risks (PSR)
Work requirements
Emotional requirement
Autonomy and room for maneuver
Social relations and relationships at work
Conflicts of professional or personal values
Economic insecurity (uncontrolled change of task, conflict, risk of losing one's job)

In this first contextual and situational analysis of human error, it is also necessary to identify the main factors affecting human performance. These factors can, in fact, influence directly or indirectly, the cognitive process developed by the operator during his activity. The objective is to identify the physical, physiological, psychological, social, chronobiological, behavioral or professional factors that favor human error. The factors identified in Tab. 1 are based on work in the field of aviation safety and in particular the Circular of the International Civil Aviation Organization (ICAO, 1993).To reach an exhaustive study, we supplemented the factors resulting from the circular of the ICAO by two other indispensable factors to the analyses: Chronobiological factors (Hadj-Mabrouk, 2016, 2017) and Factors related to psychosocial risks (Hadj-Mabrouk and Harguem, 2014).

Unfortunately, whatever the skill and the know-how of the Man, there are always errors because the human performance is intrinsically unreliable. The human operator generates errors even for simple tasks called "routine". As the complexity of the tasks increases, the associated error rate also increases

especially for complex tasks such as diagnosing critical situations. Although it is inevitable to avoid all risk situations, there are several factors that influence the error rate, positively or negatively. These factors, presented in Tab. 1, can be grouped into three broad categories:

- Individual factors that include personality, experience, competence, mood, mental and psychological ability, physical ability, and individual health factors such as fatigue, alertness, attention, stress, drugs and alcohol.

- Work factors that include the physical work environment, working conditions, conflicts of professional or personal values, autonomy and room for maneuver, the human-machine interface, the ergonomics of the workstation, the workload, the availability and quality of information and procedures, the equipment used, the requirements of the task.

- Organizational factors include organizational priorities, corporate culture, availability of resources, communication systems, social relations, workplace relationships, leadership behavior, performance indicators and economic insecurity such as the change of an uncontrolled task, the conflict or the risk of losing one's job.

These individual, professional and organizational factors are closely linked and interact together to influence human reliability. However, the interaction of all these factors can be complex and difficult to manage. It is therefore important to understand and effectively manage these performance factors by implementing well-targeted solutions to reduce the risk of human error and mitigate the severity of the consequences on the system, people and the environment. In addition, the management of these human factors should not be delegated to individual supervisors and a holistic organizational approach is essential to minimize potential risks and ensure the safety of the socio-technical system.

b. The system

At the system level, the list of potential human errors should be identified for each type of equipment. The result of this study allows the designer to take into account, from the first development phase of the system (project specification), all the potential human errors relating to each category of equipment that are likely to compromise the overall safety of the system (Fig. 4). The goal is to integrate, right from the specification and design phases of the system, the appropriate measures to catch,
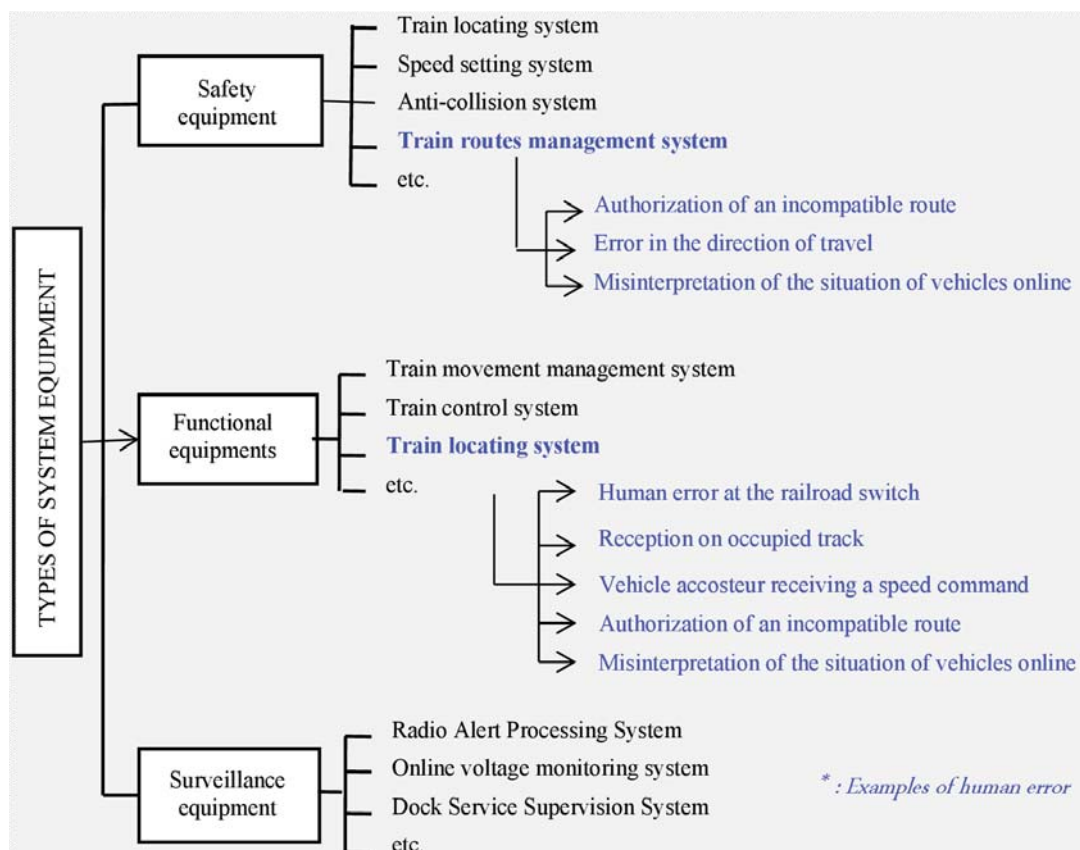

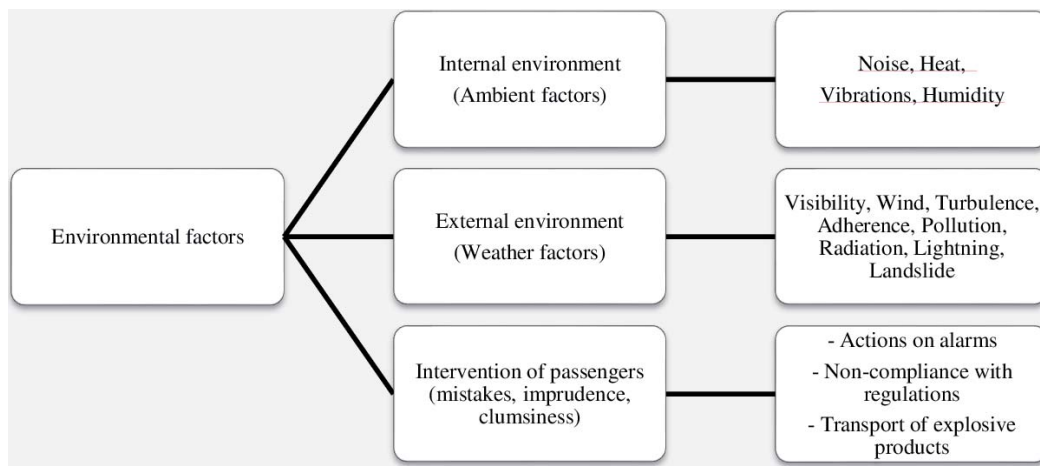Fig. 4. Examples of human errors related to the types of equipment in the system

Fig. 5. The main environmental factors favoring human error

tolerate, reduce or eliminate certain human errors. In the field of rail transport, there are generally three types of equipment: so-called critical safety equipment, functional equipment that ensures the availability of the system and finally the monitoring equipment. The purpose of the safety equipment is to replace the operation and maintenance operators of the system or to facilitate the critical tasks entrusted to them. The control systems of emergency braking equipment, collision avoidance systems and speed setting systems are examples from the field of rail transport. Monitoring equipment makes it possible to centralize information and better organize the actions of corrective or preventive interventions on the system. They contribute to improving the level of safety of the system but they do not prevent the occurrence of accidents or potential incidents. The dockside service monitoring and radio alert processing system are two examples of monitoring equipment. Functional equipment generally ensures the availability of the system. The train servo system and the train location system are two examples. Still in the context of the first phase of contextual analysis (upstream of the accident) and in order to tend towards the completeness of the analysis, it is wise to examine and identify potential human errors related to each mode of driving the system. In the field of rail transport safety, two main modes of exploitation are generally distinguished: nominal operating modes and degraded modes of exploitation.

- In the context of the nominal operating modes, we also distinguish several driving modes: the Automatic Driving without driver on board the train, the Driving in Automatic Control with driving agent (e.g. error control of doors and departure of the train), Controlled Manual Driving (e.g. traction errors, braking errors) and

finally Manual Free Driving with driving agent (e.g. driving error).

- The degraded modes of operation concern the manual driving in sight (e.g. non-respect of the spacing), the manual driving with Auxiliary Signaling (e.g. non-respect of a lateral signaling) and the driving in manual emergency mode (e.g. door control error and error on the departure of the train). Degraded modes of operation can provide operations such as berthing of trains or provisional services.

c. The environment

In addition to the human errors relating to human operators and the system, it is also necessary to identify the various environmental factors likely to influence the good progress of the human activity and in particular the execution of the prescribed task (e.g. supervision, monitoring, driving, diagnosis, etc.). There are two types of environmental hazards: internal hazards to work (environmental factors) and the external environment (meteorological factors) (Fig. 5). Identifying these environmental factors makes it possible to design and implement appropriate preventive ergonomic measures. Taking these factors into account as soon as the HMI system is designed guarantees a significant reduction in human error during the operation of the system.

d. The interactions

Contextual analysis of potential human error should also focus on the different interaction factors between human operators, between humans and the system or between humans and their internal and external environment (Fig. 6). The analysis of the interactions between the operator
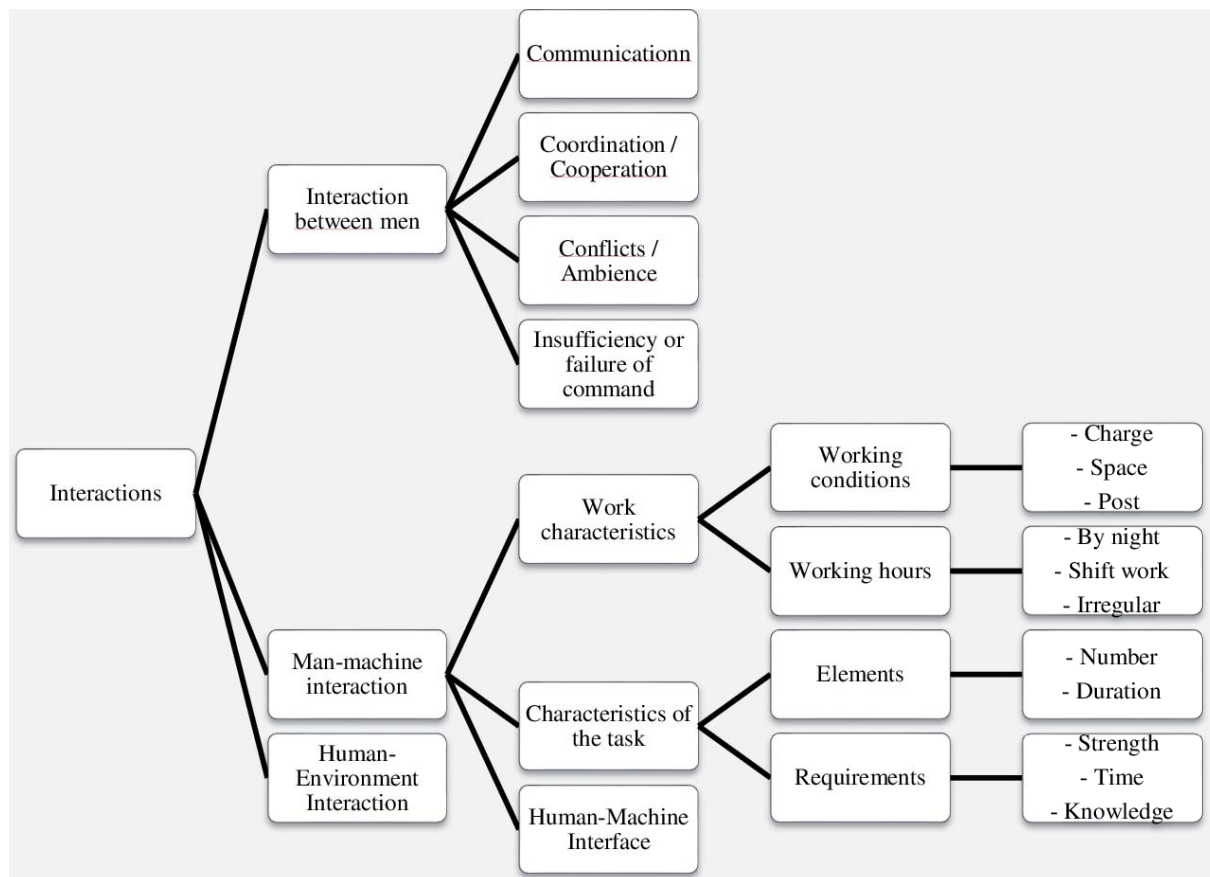
Fig. 6. Main interactions of the human operator

and the system allows the ergonomist designer to take into consideration the problems related to the characteristics of the work (load, position, schedules), to those of the prescribed task (number, duration, time, strength, knowledge ...) and those of the Human Machine Interface.

During the accident (cognitive analysis)

The second phase of analysis and evaluation of human error concerns the cognitive process involved during the accident (how?). In this context, the cognitive analysis of human error consists in studying the cognitive mechanisms involved in the production of the error at the origin of the accident. This analysis attempts to know how the cognitive process of the human operator, taking into account the contextual analysis (upstream), resulted in an erroneous action generating an accident. At this level, human errors can be classified in two different and complementary ways: 1) either by referring to the three hierarchical levels of human activity (skill-based, rule-based or knowledge-based) or 2) in the different stages of information processing human reasoning or decision-making.

Drawing on the different conceptual models of information processing, notably the works of Reason (Reason, 1990) of Rasmussen (Rasmussen, 1980, 1982, 1986, 1987, 1990) and Rousse (Rouse, 1983), Fig. 7 presents, through a simplified model but which lends itself better to an industrial application, some examples of errors (from in the safety of rail transport) relating to the different stages of information processing or problem solving. Fig. 8 summarizes the model of Rasmussen (Rasmussen, 1982, 1987) and Reason (Reason, 1990) and illustrates some examples of human error (from in the safety of rail transport) related to the human mode of operation based on skill, rules or knowledge. Nevertheless, it should be noted that the same potential error of the operator (for example: The driver does not control the braking system you at the sight of a target train; Remote unexpectedly sent by the operator of CCP; Untimely delivery of the high voltage on a section being evacuated; Switching error: Reception on occupied track or route by another vehicle) can be relative, not only to one or more functional steps of solving a problem in front of a problem situation (Fig. 7), but also to one or more levels of human functioning activities
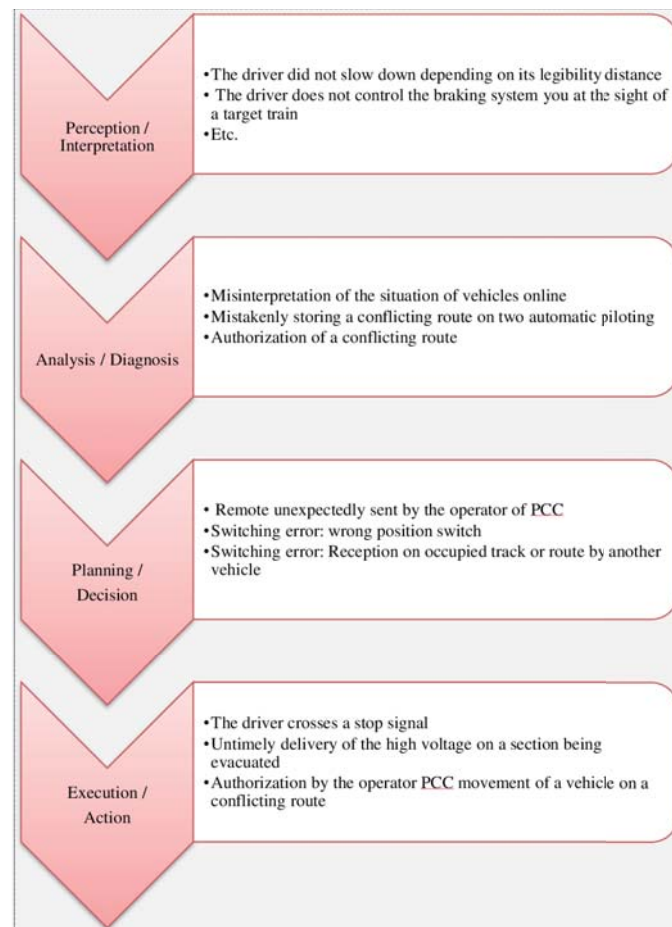
Fig. 7. Examples of Human Error in Information Processing Steps

(Fig. 8). Indeed, the reality of the field of dynamic systems proves that in the face of a critical situation, the whole cognitive process of the operator is solicited in a synchronous way and that it is very difficult to relate a human error to a precise and determined phase of the process reasoning.

Behavioral analysis (after the accident)

Behavioral analysis (after the accident) focuses on assessing the consequences of wrong action in terms of harm to humans, the environment and the system. Our study was deliberately limited to the first two levels of human error analysis involved in the field of guided or automated rail safety: contextual analysis (before the accident) and cognitive analysis (during the accident). The third level, which concerns only the analysis and the evaluation of the consequences caused by human errors, seeks to propose measures and safety barriers to minimize reduce or eliminate the risks involved. These are for example preventive measures that can be taken into account from the design phase of the system by the application of instructions and regulations strict during preventive

maintenance operations or corrective measures that can be implemented just after the occurrence of a system failure due to human error. The object being of course to avoid resorting to corrective measures by putting more emphasis on preventive measures in order to reduce the level of risk inherent to human errors and consequently to tend towards a "good" acceptable level of safety for the environment, the system and the Man.

Results

This study proposed a methodological framework for the analysis, evaluation and classification of human errors involved in railway accidents and incidents. It has identified the various factors that favor the occurrence of human errors that could lead to unhealthy situations. These factors concern not only the inappropriate behavior of human operators involved in the safety and management of railway risks, but also the technical failures of the transport system as well as the alteration of environmental conditions. Particular emphasis has been placed on factors affecting human performance
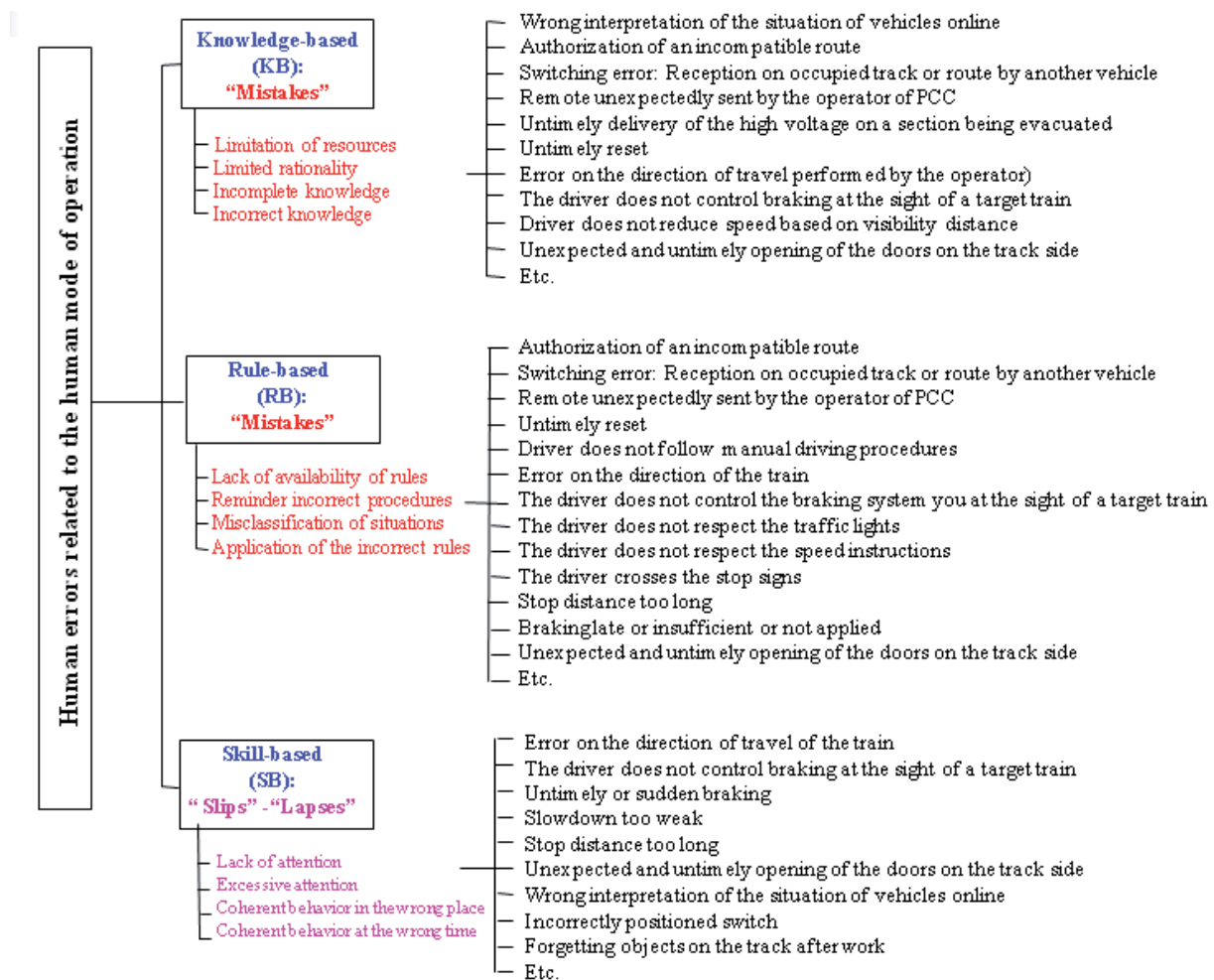
Fig. 8. Examples of human errors related to the activity levels of the human operator

such as physical, physiological, psychological, behavioral, occupational, sociological, chrono-biological, and psychosocial risk factors. These individual, professional and organizational factors are closely linked and interact to influence human reliability. It is therefore important to understand and effectively manage these performance factors by implementing well-targeted solutions to reduce the risk of error. At the system level, the designer and the safety and human factors specialists must identify and imagine (from experience feedback) the potential human errors relating to each type of equipment and in particular the critical equipment such as the safety functions that manage the speed instructions. The result of this study allows the designer to incorporate, from the first design phase of the project, the appropriate safety measures and barriers that can make up, reduce or eliminate the potential for errors. In addition to the human errors related to human operators and the technical failures related to the system, it is also necessary to identify the various environmental factors (internal

and external) likely to influence the smooth running of human activity during the execution of the project an essential or critical task of safety. The proposed approach also takes into account the different interaction factors between the human operator, the system and its environment. Taking into account these interactions makes it possible, for example, for the ergonomics designer to take into account the problems related to the characteristics of the work (load, position, schedules), the characteristics relating to the prescribed task (number, duration, force, knowledge) and finally the characteristics related to the man-machine interface. This first level of analysis, which deals with the study of the three main components of a socio technical system (man, system and environment), concerns the contextual analysis of human error and focuses on studying the different working conditions promoting the production of human error. This first level of analysis thus makes it possible to determine the local factors at the origin of the error and also to identify the different interactions that the man

undergoes with his working environment, with the other operators and with the system. The second phase of the proposed study focuses on the actual evaluation of human error and therefore concerns the cognitive process involved in the accident. In this context, the cognitive analysis of human error consists in studying the cognitive mechanisms involved in the production of the error at the origin of the accident. Taking into account the first contextual analysis (upstream of the accident), the second level of the proposed method focuses on examining and understanding how the cognitive process of the human operator has led to an erroneous action contrary to safety may cause an accident or incident. Inspired in particular by the works of Reason, Rasmussen and the HFACS system, we have agreed to classify human errors in two different but complementary ways. The first approach to classifying human error is based on the analysis of the different stages of information processing or problem solving (Perception / Interpretation, Analysis / Diagnosis, Planning / Decision and Execution / Action). The second approach to classifying the error refers to the three hierarchical levels of human activity (skill-based, rule-based or knowledge-based). To show the feasibility and the merits of the proposed study, we used several examples of human error resulting from rail transport systems put into service in France. The proposed approach allows safety managers and railway accident and incident investigation agencies to identify weaknesses in the system and to implement targeted interventions, based on all of the above-mentioned data, which will reduce the probability of occurrence of railway accidents and incidents.

Conclusion

With the increasing complexity of industrial systems and especially guided or automated rail transport systems, considerable evolutions have taken place in the way of thinking and understanding the role and place of man in the safety of human-machine systems. In this context, human factors play an important role in safety analyzes and especially after the occurrence of accidents (feedback of experience) that sometimes lead to human losses and the destruction of the environment and system equipment. It is therefore necessary to implement a process of feedback of experience (Rex) to memorize and capitalize all accidents and incidents and therefore avoid at least the reproduction of new accidents similar. The main purpose of the "Rex" is to analyze the circumstances leading to the realization of unintended adverse events. It is a dynamic process of collecting, storing, analyzing and using data related to unhealthy situations. Its purpose is to take advantage of the lessons learned to improve the level of safety by implementing the appropriate preventive and corrective measures to avoid the reproduction of such a risk-bearing situation. However, in the majority of sectors and in particular the rail transport sector, the feedback of experience (Rex) faces several obstacles and in particular the formal and systematic failure to take into account human factors in the analysis and evaluation of surveys following an accident such as a collision or derailment of a rail transportation system. The "Rex" and generally limited to a purely technical dimension and yet, in almost all high-risk sectors, statistics show that human error is the basis in 70 to 90% of cases of accidents or incidents. Admittedly, there are limits to human operators perceptually for the acquisition and processing of information and on the physical plane for the execution of the resulting actions. The variability of the skills of human operators (HO), the complexity of the transport system and the lack of flexibility of the information system are all factors that increase the difficulty of the tasks of supervision and action of the HOs. It is still a long way from the time when HOs would no longer play a role in the safety of rail transportation systems, and the risks would only come from errors in the design and implementation of systems. Indeed, the complexity and originality of the new transport systems give HOs a decisive role in the safety of train movements. The success of the human operator in accomplishing a driving task depends on several factors. It depends on, among other things, its perceptive and cognitive capacities, the validity of the various mental models that it has forged from the system, its psychological state, its workload, the complexity of driving situations and its state stress, for example in emergency situations where safety is threatened. Despite the advent of automation, the human operator remains the key element of the transport system and remains indispensable. Sometimes, its action is the only defense to prevent a failure of automation becomes an accident. The human operator is a paradoxical element: in a stress or fatigue situation, it can be an element of the loss of the reliability of a system. However, in certain critical situations of insecurity, it can be a factor of reliability, by restoring the good functioning of the system, sometimes by actions not envisaged by the regulation of safety of the exploitation but, related to his knowledge, his experience and his know-how; it then catches errors made by the designer. It is therefore necessary to optimize the place of the man in the transport system in full knowledge of his capacities but also of his limits. The selection and training of men is no longer

sufficient to achieve the expected performance. To achieve better controlled performance of the transport systems, it is necessary to design error-tolerant systems, to specify the contribution of HO in a system, to better organize and structure the feedback and to analyze the workload. It is also necessary to develop decision support tools, to develop systems whose functionalities give HOs flexibility and adaptability, to understand HOs in nominal and degraded situations, to identify ways to improve the work situation in order to prevent negative consequences and favor positive consequences. In short, human factors must be integrated from the specification of needs and the design of the system to design systems that adapt to HOs and not the opposite. In order to meet the requirements expressed by French and European rail safety regulations, and in order to comply with the harmonization measures recommended by the European Directive on the safety of the Community's railways, our contribution has been translated into the proposal of a global methodological approach to experience feedback (Rex) centered on the analysis of human error in the accident. Inspired in particular by the works of Reason and Rasmussen, the approach of analysis of human error that we have elaborated involves three levels of complementary analysis:

- The first level of contextual analysis (before the accident) makes it possible to study the various factors favoring the production of the human error at the origin of the accident. These factors relate to the human operator, his work environment, the system and the various interactions of humans with the system and the environment;

- The second level of cognitive analysis (during the accident) aims to identify human errors related to the human cognitive process involved in a given situation of insecurity;

- The third level of behavioral analysis (after the accident) focuses on assessing the consequences of wrong action in terms of harm to humans, the environment and the system.

In order to demonstrate the feasibility and the validity of this new approach, we have used some real examples from the field of railway safety and in particular the TGV-Nord high-speed system, the driverless metro type ALV (Automatic Light Vehicle), the Maggaly system from Lyon and the Transmanche Fixed Link system. In our opinion, the main contribution of this approach lies in the identification of the main concepts relating to the human operator, to be taken into account as early as the data collection and analysis phase after an accident or a railway incident (experience feedback). This approach also makes it possible to specify, at each level of analysis, a list of potential human errors that contribute to the occurrence of railway accidents and that must be taken into account in the experience feedback (REX) to improve the level of safety of the new transport systems. Finally, this contribution makes it possible to respond European regulations and directives whose primary objective is to formally and systematically integrate human factors into railway safety analyzes. Nevertheless, this approach requires its implementation in other real industrial conditions, in order to validate and, if necessary, improve what remains a proposal.

References

Amalberti, R. 2001. Human error in perspective, Risks errors and failures: an interdisciplinary approach (Amalberti, R., Fuchs, C., Gilbert C.), Publications of the MSH-ALPES, 71-106. (In French)

Amalberti, R., Barriquault, C. 1999. Foundations and limits of experience feedback. Annals of Bridges and Roads, 91: 67-75. (In French)

Cellier, J-M. 1990. Human error in the work, Human factors of reliability in complex systems (Leplat J. and De Terssac G.), Octares edition, 193-209. (In French)

ICAO, 1993. Circular No. 240-AN / 144. Human Factors: Investigating Human Factors in Accidents and Incidents, 39-44. (In French)

De keyser, V. 1982. Human Reliability in Continuous Processes: Introductory Report, Mental Activities in Highly Automated Production Processes, 17th day of SELF, human work, 45 (2): 331-339. (In French)

Directive (EU) 2016/798 of the European parliament and of the council of 11 may 2016 on railway safety.

Ergai, A., Cohen, T., de Sharp, J., Wiegmann, D., Gramopadhye, A., Shappell, S. 2016. Assessment of the Human Factors Analysis and Classification System (HFACS): Intra-rater and inter-rater reliability, Safety Science, 82: 393-398, Available at: https://doi.org/10.1016/j.ssci.2015.09.028.

Fadier, E. 1994. The state of the art in the field of human reliability, Ed Octares. (In French)

Fu,G., Cao,J-L., Zhou, L., Xiang, Y-C. 2017. Comparative study of HFACS and the 24 Model accident causation models, Petroleum Science, 14 (3): 570-578, Available at: https://doi.org/10.1007/s12182-017-0171-4.

Gilbert, C. 2001. Experience feedback: the weight of constraints, Annales des mines, 1: 9-24. (In French)

Hadj-Mabrouk, H. 2016. Contribution of Human factors and chronobiology vigilance in public transport safety in France, Magazine on The Rail Industry of India, 1 (2): 49-52.

Hadj-Mabrouk, H. 2016. Machine learning from experience feedback on accidents in transport. Published in 7th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications, 246-251, DOI: 10.1109/SETIT.2016.7939874, Available at: http://ieeexplore.ieee.org/document/7939874/.

Hadj-Mabrouk, H. 2016. Contribution of chronobiology vigilance in public transport safety. Journal of Multidisciplinary Research and Development, 3 (9): 214-221.

Hadj-Mabrouk, H. 2017. Impact of human errors and hypo-vigilance on transportation safety, International Journal of Research in Engineering and Technology (IJRET), 6 (1): 01-06, Available at: https://doi.org/10.15623/ijret.2017.0601001.

Hadj-Mabrouk, H., Harguem, B. 2014. Psychosocial Risk Analysis and Assessment Method Based on Feedback from Experience, The Psychosocial Risks books, 23: 14-18. (In French)

Hadj-Mabrouk, A., Hadj-Mabrouk H. 2003. Approach of integration of human error in the feedback of experience. Application to the field of rail transport safety, Ed Inrets/Lavoisier, 107. (In French)

Joing, M., Keravel, F. 1993. Experience feedback and analysis of the human factor. General Review of Railways, 5-8. (In French)

Leplat, J. 1989. Human error in question: Cognitive analysis, psychopathological implications, Rev. de Méd. Psychosom, 20: 31-40. (In French)

Madigan, R., Golightly, D., Madders, R. 2016. Application of Human Factors Analysis and Classification System (HFACS) to UK rail safety of the line incidents, Accident Analysis & Prevention, 97: 122-131, Available at: https://doi.org/10.1016/j.aap.2016.08.023.

Norman, D.A. 1983. Design rules based on analyses of human error, communication of the ACM, 26 (4): 254-258.

Punzet, L., Pignata, S., Rose, J. 2018. Error types and potential mitigation strategies in Signal Passed at Danger (SPAD) events in an Australian rail organization, Safety Science, 110 (Part B): 89-99, Available at: https://doi.org/10.1016/j.ssci.2018.05.015.

Quatre, M. 1999. Experience feedback in severe land transport accidents, Annals of Bridges and Roads, 91: 17-22. (In French)

Rasmussen, J. 1987. The definition of Human Error and Taxonomy for technical system design, New Technology and Human Error (Rasmussen J., Duncan K. and Leplat J.), Wiley John & sons, 23-30.

Rasmussen, J. 1980. What can be learned from human error reports? in: Duncan K., Grunuberg M and Dallis D. (Eds), Changes in Working Life, (Wiley, Chichester), 97-113.

Rasmussen, J. 1982. Human errors: a taxonomy for describing human malfunction in industrial installations; Journal of Occupational Accidents, 4: 311-335.

Rasmussen, J. 1986. Information Processing and Human-machine Interaction: an approach to cognitive engineering, New York, North - Holland series in system science and engineering, 12, Ed. Sage A.P.

Rasmussen, J. 1990. The role of error in organizing behavior, Ergonomics, 33 (10/11): 1185-1199.

Reason, J. 1990. Human error. Cambridge University Press (New York, USA). ISBN 9780521314190.

Reinach, S., Viale, A. 2006. Application of a human error framework to conduct train accident/incident investigations, Accident Analysis & Prevention, 38 (2): 396-406, Available at: https://doi.org/10.1016/j.aap.2005.10.013.

Rouse, W.B., Rouse S.H. 1983. Analysis and classification of human error, IEEE Transactions on systems, man and cybernetics, 13 (3): 539-549.

Salminen, S., Tallberg T. 1996. Human error in fatal and serious occupational accidents in Finland, Ergonomics, 39 (7): 980-988.

SanKim, D., ChulYoon, W. 2013. An accident causation model for the railway industry: Application of the model to 80 rail accident investigation reports from the UK, Safety Science, 60: 57-68, Available at: https://doi.org/10.1016/j.ssci.2013.06.010.

Swain, A-D., Guttmann, H-E. 1983. Handbook of human-reliability analysis with emphasis on nuclear power plant applications. Final report. United States. DOI: 10.2172/5752058.

Van-Eslande, P. 2000. Human error in accident scenarios: cause or consequence? The Transport Research Journal, 66. (In French)

Wibaux, F. 1995. Feedback from experience: what lessons to draw from human errors. Aeronautical and Space Medicine Review, 136: 251-255. (In French)

Wiegmann, D., Shappell S. 2003. A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System, London, Routledge, ISBN 9781351962360, 184 pages.

Zhan, Q., Zheng, W., Zhao, B. 2017. A hybrid human and organizational analysis method for railway accidents based on HFACS-Railway Accidents (HFACS-RAs), Safety Science, 91: 232-250, Available at: https://doi.org/10.1016/j.ssci.2016.08.017.

Zhou, J-L., Lei, Y. 2018. Paths between latent and active errors: Analysis of 407 railway accidents/incidents' causes in China, Safety Science, 110 (Part B): 47-58, Available at: https://doi.org/10.1016/j.ssci.2017.12.027.