On the Study of Human Reliability in Transportation Systems of Systems

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Abstract – *Humans are and will remain one of the critical constituents of a technological system. The study of Human Factors is a broad domain with equally varying applications. Quantification thereof with a Human Reliability Analysis (HRA) poses considerable challenges and advantages. In increasingly complex modern systems where large resources are allocated towards ensuring system's operational safety, it becomes necessary to analyze the actions of human operator who directly or indirectly influences system safety. This paper tries to establish a base towards a HRA model, to address existing issues. Railway systems and Advanced Driver Assistance Systems for automobiles are our application domains; we aim to identify the need of and usability in both. Human considered as a component of the System of Systems for risk assessment will allow us to study its impact on system reliability and give feedback to improve system safety.*

Keywords: Human Reliability Analysis, System of Systems, Rail transportation, automobile, ADAS

1 Introduction

Human Reliability Analysis (HRA) involves determining the probability of successful performance of the human activities necessary to make a system reliable. HRA models were designed because of increasing involvement of humans in accidents and an absence of methods to detect their risk towards the safe operation of the system [1]. It is a quantitative technique aimed at identifying the probability of occurrence of human error, what is known as Human Error Probability (HEP) [2]. System wide Probabilistic Risk Assessment (PRA) also benefits from the HRA calculations providing with quantifiable results to system safety assessment including human factor considerations. This gives to means to assure the authorities and the public that the overall risk is under acceptable limits.

Advanced Driver Assistance Systems (ADAS) are systems developed to assist and complement the driver in the complex process of controlling a road vehicle. The components and features of the system can differ between manufacturers and component suppliers; in general it refers to a pretty large family of driver aid products. The general aim of such a system is to reduce or eliminate driver errors and increase efficiency and safety in road transport. It is one of the fastest growing application areas in road vehicles.

Rail transportation has multiple entities all contributing towards a safe and efficient transportation system. It is composed of multiple human actors (driver, traffic control, maintenance personnel, operational management) and signaling systems working collectively. The European Rail Traffic Management System (ERTMS) is a major "European industrial project" to enhance cross-border interoperability by creating a single Europe-wide standard for railway signaling. It is composed of the European Train Control System (ETCS), a standard for train control and GSM-R, the GSM mobile communications standard for railway operations. Standardized signaling systems such as ERTMS provide a good application domain as it aids in a wide acceptance of methodologies proposed around it.

This paper aims to present the roadmap towards the integration of human factors in risk assessment of transportation systems of systems. Section 2 of this paper will discuss the need to include human reliability in such a task. The importance of its quantification is also discussed in the same section. Section 3 consists of a brief description of some selected HRA models and works relevant to our application. The challenges associated with proposing a HRA model and our proposal for such a methodology are discussed in Section 4. The paper is concluded in Section 5 with some remarks and conclusions.

2 On the importance of the study of Human Reliability in SoS

The complex the system becomes the difficult it is to identify the reliability of the subsystems (including a human). A SoS view provides with adequate directions to handle this problem. Human - studied as part of a technological system for example a train or a car driver, a rail traffic manager etc. does exhibit most properties expected from the constituents of a System of Systems

(SoS) [3]. When we consider human controller as a component of the system it exhibits autonomy, operational independence and induces emergent properties [4], co-operating with other components towards a common goal. Therefore for most cases, interacting systems in general involving a human user at some level in the system can be treated as a SoS. Furthermore the application domains that we are dealing with, Railway signaling systems ERTMS in particular have been shown to possess the properties expected from SoS in [5]. A road vehicle with embedded control systems (constituents of an ADAS) also exhibits properties of a SoS [6]. Accident analysis sometimes reports an unforeseen interaction of subsystems (involving a human) as the cause of system failure. This relates to the emergent properties exhibited by a SoS. The absence of adequate methods to describe and analyses such properties makes it difficult to find such evolution of events.

Many studies and reports have shown that in railway human error is often the leading cause of an accident. More recently a study [7] states that at least 75% of fatal railway accidents in Europe between 1990-2009 were due to human errors. However an Australian study of over 100 rail accident reports found that errors attributed to human factors were caused by the conditions in which drivers had to work, indicating driver errors were in fact consequences of the problems, not the initial issue [8]. Some call for inclusion of an analysis or specific certification requirements in rail transport [9]. This also affect the design of the system as human considerations are not imposed and the system is conceived with an independent design perspective, which further adds to overall risk during system operation by a human [9]. A quantifiable HRA model will give engineers and certification authorities means to reduce such statistics. The domain of road transport lacks HRA techniques when compared to railways and aviation, albeit human errors are one of the major causes of most road accidents. Various researchers and industrial stakeholders are realizing the importance of human factors for ADAS [10],[11]. This work will try to provide as general results as possible to provide methods applicable in both the domains. It is hence needed on one part for a method to identify relevant factors and secondly quantification of those factors to take evidence-based decisions. Such a work will permit engineers and designers to understand human factors affecting their system reliability and identify areas specific to human factors in which improvements are needed.

3 Some Human Reliability Analysis models and previous work

The need for HRA models originated in part to obtain accurate PRA assessments. Human factors were initially underestimated in their contribution to the overall risk of the system. With passing time and increased research, now there are various HRA models available addressing different issues. We discuss some well-known HRA models and some relevant work in this section.

Most of the HRA models proposed and used for a critical quantitative analysis of human controllers are in the nuclear domain and have been discussed extensively in [1],[2]. Studies have also been made to investigate their applicability to other domains such as medicine [12]. Human factor experts often broadly classify models into two generations: HEART (Human error assessment and reduction technique), THERP (Technique for Human Error Rate Prediction) among other task-oriented models are regarded as first generation, and models factoring in the environment/context like ATHEANA (A Technique for Human Event Analysis) are considered to be second generation. Experts believe human factors are not to be considered in isolation: environment, cognitive state and limited experimental data among other ambiguities are needed to be addressed [13].

Ergonomics and human factors are often used interchangeably in the railway domain and have attracted large part of the research. A review study of these factors [14] indicates the increasing interest of railway stakeholders in understanding human factors. A work having similar objectives [15] proposed an HRA model called Human Performance Railway Operational Index (HuPeROI). It allows the estimation of HEP for railway operations based on a taxonomy of rail specific Performance Shaping Factors (PSF) [16]. Researchers in [17] focused on the importance of PSFs towards proposing a context related HRA model for rail systems. They further remark that different national railway standards lead to inapplicability of such studies in different countries. This can be tackled by our consideration of ERTMS, especially when dealing with train driver’s onboard control systems. European Railway Agency (ERA) commissioned an in-depth study of human factors integration in European railways [18]. This work identified components of systems that need more attention towards human work and performance. It however focused on functional analysis and did not take a critical risk analysis point of view. An HRA technique was also developed over at Rail Safety and Standards Board (RSSB) called Railway Action Reliability Assessment. It is centered on quantifying HEP values associated with each task and the PSF influencing that particular task [19]. They further note that their technique can be used for risk or safety decision making in cases where data (e.g. from real accidents or simulator trials) is not available. This addresses a recurring problem (accuracy of the obtained quantification) on the validity of HEP methods and needs further investigation. Network Rail’s (authority responsible for United Kingdom's railway network) Ergonomics Group commissioned the development of a tool to help assess the drivability of rail network schemes at an early point in their development [20]. ERGOTOOLS, the resulting toolkit, allows determining workload (signaler and driver) and operational roles. A study evaluating two human error identification techniques [21] concluded that the task of error identification needs local (national) considerations and appropriate context relevant definition of terms in order to be usable for accident reviewers. Furthermore some tools might only be usable for the domains they are developed. An approach proposed in [22] gives a compelling method to perform an human reliability and error analysis. The difference in our work is on two main points; first is our focus on quantification of human factor risk. Secondly the propagation of that risk to system level will, in our opinion, give better feedback results to reduce it. System failure as an emergent property can be used to analyze the risk induced by human on the system of systems. One work [13] although done from a nuclear domain standpoint does list some interesting desirable characteristics of HRA models, notably applicability to different problems, a procedure for quantitative results and the need for a model-based approach. Some of these issues we will try to address in our work.

4 Challenges of human reliability assessment in transportation SoS - towards a more formal method

The concept of human reliability confronts the problem of its definition. First, it can be defined as technical reliability, i.e. the ability of a (human) component to realize its allocated functions successfully, in given operational conditions and during an interval of time. A measurement of this ability is usually the probability of success. However, this definition is not sufficient [23]. The human reliability is not static but evolves dynamically regarding learning effects and cooperative activities [24], and its assessment is rather multi-criteria than mono-criterion. It usually relates to tasks to be achieved by human operators instead of functions and to the characteristics of these tasks and of the human resources [25].

The human characteristics are the human constraints for achieving tasks. There are constraints such as: humans seen as a whole component or are composed of separate sub-components; humans are overloaded or under-loaded; humans are hypo-vigilant; humans are not experienced etc. Some of these characteristics relate to the so-called PSFs. These factors that may affect the system performance are numerous and correlations between factors have to be identified in order to simplify their integration into a human reliability assessment. Moreover, the main difference between humans and machines is the possibility that humans do not respect voluntarily a given prescription for specific reasons due to organizational factors for example, or to create new tasks or functions by using differently the technical resources [26]. In such cases, humans are not repaired or changed, but they adapt their own behaviors to specific or usual constraints they have to control. Therefore, the definition of human reliability may be adapted as the ability of a human component to: 1) realize successfully the prescribed tasks in given operational conditions during an interval of time or at a given time and 2) not to realize additional task that may affect the performance of the human-machine system in terms of, for instance, safety, production, quality, or workload [23]. The measurement of such ability leads to new challenges because it integrates not only the probability of success of the prescribed task achievement but also the probability of success of the possible additional task achievement, integrating the correlations between technical, human and organizational factors.

On the other hand human reliability assessment can have several sources of explanation [23]: the assessment made by the designers of a given human-machine system, the assessment made by an industrial organization that will employ people in order to operate this system, and the assessment made by the users of such a system. Sometimes these assessments differ. The feedback of experience is then required in order to integrate the natural learning effects of human operators into the design process and to take into account the behaviors applied for controlling well-known or unprecedented situations. Joint prospective, retrospective and on-line approaches are useful in order to guarantee the efficiency of the human reliability assessment. Evidential networks or Bayesian networks can then be suitable tools to support such assessment [27],[28].

Working with the framework of ERTMS will allow this work to be widely applicable in the railway industry. We need to identify and analyze factors which also affect human-ADAS interaction to find a common ground between both the application domains. This can be achieved by considering the car/train driver as the subject. The context and experimental results need to be considered separately but the factors and framework of quantification can be common. However adapting our quantification for rail and automotive domain poses a considerable challenge. Quantification of human reliability are critiqued frequently by experts, first for being domain-specific and secondly for accuracy of data (due to the lack of it) [29]. Expert opinion using questionnaires and/or experimental simulations are the sources we aim to use in our work. This data needs to be rigorous for the model to provide accurate results. Expert opinions depend upon an expert’s personal experiences and beliefs. Furthermore experimental data on simulations run in labs by its very nature cannot accurately represent the real-world conditions; such inaccuracy needs to be taken to account.

4.1 A Formal method for HRA evaluation

A formal framework is needed to obtain a numerical value of the system risk. This is needed for (including but not limited to): evaluation of environmental effects (PSFs and other), calculation of HEP and estimation of risk at system level. Figure 1 gives an overview of the steps of methodology which we aim to propose.

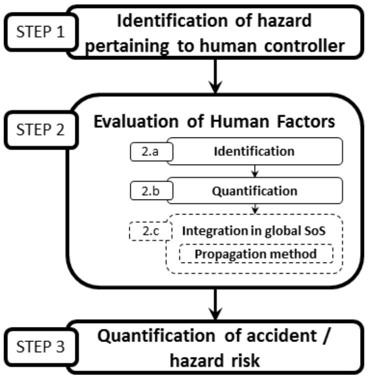
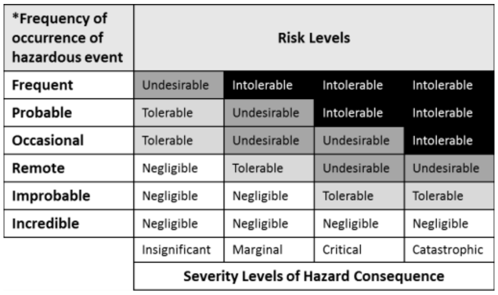


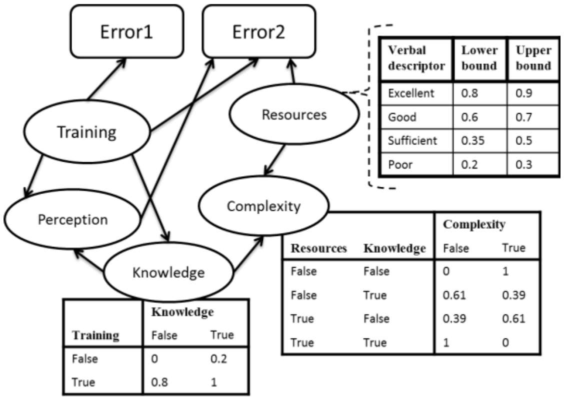
Figure 1. Overview of proposed methodology

In *Step 1* and *Step 2.a.* we take inferences from works where identification of safety relevant activities related to human factors have been done [18] among others, taking notes from their methodology to map high level 'purpose/goals' onto the 'human function goals'. Most human error identification (accident analysis) studies can also act as starting points for this activity. Identifying significant factors which effect human performance is a challenge in its own right; however we do not tackle it as part of current work. *Step 2.b.* will cover the work towards quantification of selected human factors. The usage of experimental data from simulations as discussed before inevitably creates a state of uncertainty on HEP values. Furthermore it is safe to assume that while accounting for the PSFs we might have a reasonable degree of uncertainty as well. This is because it is difficult to quantify absolute values on how certain conditions affects different humans, even for experts. Hence here we aim to use a graphical model, based on uncertainty theory and belief functions for our calculations. We will start off with a simple model of Error and PSFs represented by a graphical model, a Bayesian network or some similar framework introducing uncertainty later on.

Table 1. An example of Risk Matrix for risk severity [30]



*Frequency of occurrence of hazardous event	Risk Levels			
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Remote	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Negligible	Negligible	Tolerable	Tolerable
Incredible	Negligible	Negligible	Negligible	Negligible
	Insignificant	Marginal	Critical	Catastrophic
	Severity Levels of Hazard Consequence			



Verbal descriptor	Lower bound	Upper bound
Excellent	0.8	0.9
Good	0.6	0.7
Sufficient	0.35	0.5
Poor	0.2	0.3

		Complexity	
Resources	Knowledge	False	True
False	False	0	1
False	True	0.61	0.39
True	False	0.39	0.61
True	True	1	0

	Knowledge	
Training	False	True
False	0	0.2
True	0.8	1

Figure 2. Graphical model for HEP calculations

Figure 2 shows a simple example of what we aim to start off with. The quantification of an error is a function of the factor(s) associated with it. A straightforward conditional probability can be used, e.g. given that we have a good level of Training what is the probability of Error1 happening. These numbers as discussed before, we aim to get from simulator experiments and/or expert opinions. When dealing with expert opinions mostly we have linguistic indications, which we need to transform to quantitative measures for our calculations. The table associated with 'Resources' in Figure 2 shows transformation of data obtained from experts in questionnaires, to quantitative measures for our calculations. These numbers depend upon the application domain and can be aided by experimentations with simulators. In addition to that, one can calculate the impact of one PSF on another. As shown in Figure 2, a relation between 'Training' and 'Knowledge'. Such relations allow a detailed real world description of the context. Such a method will allow a multi-factor assessment of human factors: 'Knowledge' does not directly have an impact on Error2 but our proposition will allow such a calculation. Subsequently we can observe if one error's occurrence increases the likelihood of the other. It is difficult to quantify theses effects accurately even with expert opinions and existing studies, creating a need to account for uncertainty in our calculations. Valuation-based Systems (VBS) [31] permits handling uncertainty in calculations related to relations between variables, making it useful in dealing with the relations between PSFs.

A simple addition of likelihood of individual errors of the system components to calculate risk at the system level will not give accurate results. We need a more comprehensive method to account for their severity towards the system's criticality of failure. *Step 2.c.* will lead to results for an 'outward propagation' of previously calculated human factor risk. VBS permits modeling systems and their interactions as well as the propagation of uncertainties related to the occurrences of events changing the behavior of the system. This propagation method will allow analyzing the risk incurred at the system level. Employing such a rigorous methodology remains long term goals of our work. Initially we will calculate system level risk as simple function of the likelihood of the human error (HEP calculated in previous step) and the severity of that error. Information on the severity of the error will be obtained as a risk level from a given risk matrix. An example shown in Table 1 is of a classic risk matrix for determining the severity of a hazard for the system under scrutiny. Subsequently one will be able to observe the impact of a specific human factor risk on the overall system safety in *Step 3*. This task is equally important as it will result in numerical evidence to provide specific recommendations to reduce risk, viz. which factors are important and induce highest risk on the system. Finally after obtaining system level risk we aim to provide a feedback of sorts to mitigate the human error in order to increase overall system safety. This can lead to arguments of reduction in individual component-level safety barriers for the SoS. All while maintaining the overall system reliability.

We will begin initially with a select few factors and try to complete all the steps of our methodology, addressing the framework development along the way. One this initial loop is complete more factors can be added and an extensive data collection can begin to provide an accurate quantification. To validate our proposed methodology, a system of systems A may be compared with a system of systems B using the same method. Even if this method is not perfect, the error of assessment for the first system will be the same for the second one. We can then work on the probability of success or failure of a function allocated to humans or machines or to both humans and machines. An example of such approach can be found in [32].

5 Conclusions

Human remains at center of both rail and road transportation by their very conception and hence the need to increase the safety of these systems calls for addressing human reliability. This paper tries to establish a base towards the need of a human reliability analysis (HRA) model for transportation systems, railway systems and advanced driver assistance systems in particular. It identifies the challenges and gives a broad overview of the proposed methodology.

All through the development considerations will be made so that our model can be used for any kind of SoS involving a human interacting with the system. To handle two levels of uncertainty, first in human error probability values, second in context or environmental effect on the human, we aim to use a belief functions and uncertainty theory based framework. The actual model is not proposed as part of this work; however that is our eventual goal. Our future work will involve starting off with some selected factors and to determine their risk at system level. The level of human integration in modern technological system is becoming increasingly complex, calling for inclusion of human in SoS reliability analysis. This point of view of this work will, we believe, provide novel risk quantification methods, to evaluate the risks at SoS level resulting from different human-machine cooperation mechanisms. To gather data for calculation we aim to use ERTMS/ETCS on-board simulator at Université de Technologie de Compiègne for railway and car driver simulator at Université de Valenciennes for ADAS.

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