Monte Carlo Simulation for the Level Crossing Imprecise Reliability Evaluation

Jaouad Boudnaya, Abdelhak Mkhida and Mohamed Sallak

March 11, 2020

Monte Carlo Simulation for the Level Crossing Imprecise Reliability evaluation

JAOUAD BOUDNAYA[1], ABDELHAK MKHIDA[1], MOHAMED SALLAK[2]

j.boudnaya@gmail.com, abdelhak.mkhida@gmail.com, sallakmo@utc.fr

[1] ENSAM Meknes, Laboratory of Mechanics, Mechatronics and Control (L2MC), Marjane 2, PO Box 15290, Al-Mansour Road Agouray, 50500 Meknes, MOROCCO

[2] Sorbonnes Universities, Compiegne University of Technology, Heudiasyc Laboratory, CNRS UMR 7253, Research Center of Royallieu, 60200 Compiegne, France.

Résumé :

Ce papier présente une méthodologie pour évaluer la fiabilité imprécise des systèmes de passages à niveau marocains à l'aide d'une approche de simulation de Monte Carlo de second ordre avec l'intégration du facteur humain et l'incertitude des données des défaillances (incertitude aléatoire et épistémique). Il repose sur une méthodologie permettant de propager séparément les incertitudes aléatoires et épistémiques afin d'obtenir la distribution imprécise de la fiabilité du système de passage à niveau en fonction du temps. Nous proposons également l'influence du nombre de simulation sur les résultats de la fiabilité et le critère d'arrêt de la simulation.

Mots clés – *Simulation de Monté Carlo, Passage à Niveau, Fiabilité, Facteur Humain, Incertitude.*

Abstract :

This paper presents a methodology to evaluate the imprecise reliability of the Moroccan Level Crossing systems using a second-order Monte Carlo Simulation approach by integrating human factor and failure data uncertainty (aleatory and epistemic uncertainty). It is based on a methodology to propagate separately aleatory and epistemic uncertainties to obtain the imprecise reliability distribution of the level crossing system over the time. We propose also the influence of the number of simulation to the results of the reliability and the simulation stopping criterion.

Keywords - Monte Carlo Simulation, Level Crossing, Reliability, Human Factor, Uncertainty.

1 INTRODUCTION

The railway safety is one of the most complex problems which are necessary to approach in order to estimate better and improve the performances of the railway systems. Indeed, the level crossings constitute the major source of the risks of accidents in the railway domain in Morocco.

The approach of this work is based on Monte Carlo Simulation Method, which encompasses a large number of algorithms whose defining characteristic is the use of random numbers. As such, these algorithms are non-deterministic; however, their use is not constrained to probabilistic models. They can be described as "statistical simulation methods", because they provide solutions by performing statistical sampling.

In this paper, we evaluate the Moroccan level crossing reliability distribution over the time and the reliability values using Monte Carlo simulation by integrating human factor, and failures data uncertainties. We identify also the influence of the number of simulation to the results of the level crossing reliability as well as the stopping criterion of the simulation.

2 REVIEW OF LITERATURE

Several works related to this problem were presented in the literature. In the paper **[1]**, the authors examine driver situation awareness at rail level crossings using a network analysis-based approach and analyze revealed key differences between novice and experienced drivers situation awareness by proposing a series of wider driver behavior applications. In the paper **[2]**, the authors analyze the functional interactions between the existing level crossing functions and any new technological system in terms of reliability, so as to choose asset owners wishing to upgrade and improve the existing systems reliability. The study presented in **[3]**, shows an overview of the challenges of level crossings to shared high-speed rail passenger and heavy-axle-load freight operations in the U.S. This study is expected to identify and evaluate the principal technical challenges related to level crossings in developing high-speed rail systems so as to facilitate the planning, development, construction, and operation of new systems. The purpose of the work discussed in **[4]** is to improve safety of level crossing by analyzing accident/incident data bases and integrating human behavior using UML diagrams, in order to bring out the main functions of level crossing protection system which are concerned by different actors of the project. The paper **[5],** presents a probabilistic method that accounts for the variations of the component design variables of sight distance at level crossings so as to evaluate system reliability. The method is validated using Monte Carlo simulation. The proposed method should result in safer operations at railroad grade crossings. The paper **[6],** gives an insight view of translating the sequence of event to model pedestrian level crossing scenarios using Petri Nets approach. The developed model gives an understanding of the risky situation when pedestrian and vehicle are interacted at signalized intersections. Further analysis of this model is expected to give a potential risk value of pedestrian level crossing. In **[7],** level crossings are modeled by p-time Petri nets in order to satisfy time specifications defined in safety requirements of railway systems. In **[8],** the authors propose a global model of the level crossing implying at the same time the rail and road traffic by using stochastic Petri nets. This model is obtained by a progressive integration of the developed elementary models; each of them describes the behavior of a section. It allows the follow-up and the qualitative and quantitative evaluation of the effect of various factors on the level of the risk. The paper **[9]** discusses major obstacles for the adoption of low-cost level crossing warning devices (LCLCWDs) in Australia and reviews those trailed in Australia and internationally. The argument for the use of LCLCWDs is that for a given investment, more passive level crossings can be treated, therefore increasing safety benefits across the rail network. In 2017, the authors of the paper **[10]** evaluated level crossings system risk assessment by Fault Tree Analysis and Event Tree Analysis and indicated their applicability to the Slovakian railways. The risk assessment models are based on the accident scenarios**.** In the paper [**11],** some Level Crossing accident prediction models are developed and some impacting parameters are evaluated. The Ordinary Least-Squares (OLS) and Nonlinear Least-Squares (NLS) methods are employed to estimate the respective coefficients of variables in the prediction models, based on the Level Crossing accident/incident data. In the paper **[12],** Larue shows the need for development of interventions at urban level crossings targeting violations for all types of level crossing users to ensure level crossings to respond to the rapid changes in the transport environment.

All these works allow the evaluation of railway system dependability, but they do not integrate at one time many parameters like imprecision and human factor.

Indeed, for a system composed of several highly reliable components, uncertainty of reliability data (failure rates) has interesting effects at the system reliability, for this reason we propose in this paper an imprecise approach.

3 MONTE CARLO SIMULATION FOR IMPRECISE RELIABILITY APPROACH

In our approach, we are going to apply the steps of Monte Carlo simulation described as follow:

1- We fix the time t = ti.
2- We do a normal distribution on the interval of failure rates [λmin, λmax] of each component j.
3- We pull λ_j and we compute the Reliability $\mathbf{R_j(t_i)=exp(-\lambda_j.t_i)}$ for each component j.
4- We compute the Reliability of the system R_s.
5- We redo steps 1 through 4 for Ns Simulation Ns=10000.
6- We record the results of the system output: Upper reliability Rmax(ti), Lower reliability Rmin(ti), the mean of the distribution μ (ti), the standard deviation of the distribution σ(ti).
7- We reconstruct the reliability distribution of the system using the probability density function of the normal distribution :

$$\boldsymbol{f(R,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}.exp(-\frac{(R-\mu)^2}{2.\sigma^2})} \qquad \textbf{(1)}$$

8- We redo steps 1 through 7 for each ti.
9- we fill the matrix of reliability distribution as a function of time and reliability D=g (t,R)
10- We draw the 3D surface representing the distribution of reliability based on the values of ti and R(ti).

The **figure 1** summarizes the algorithm of this simulation for level crossing reliability.

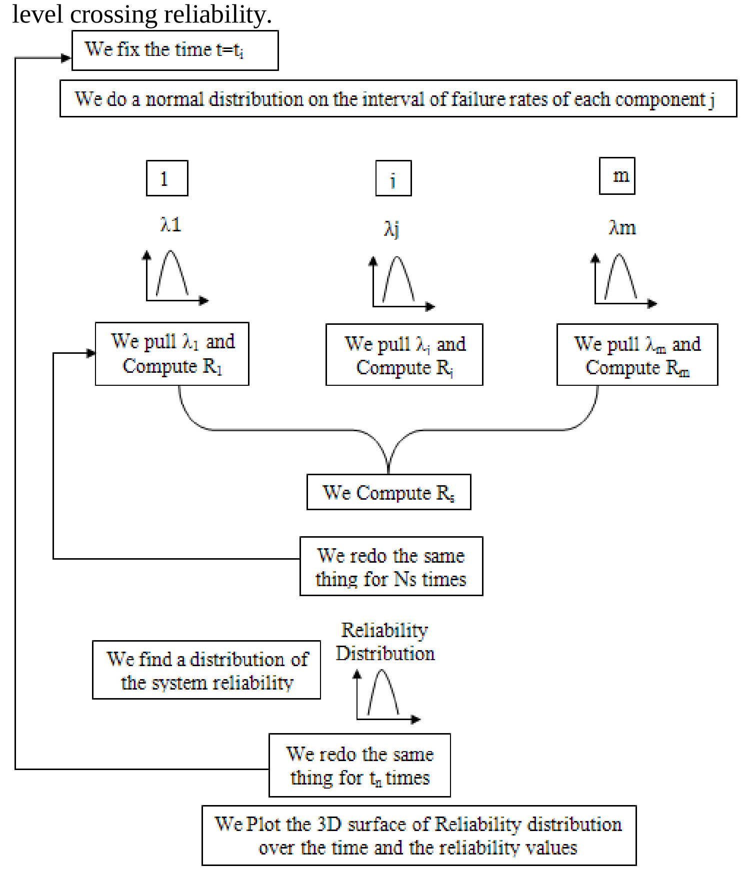

Figure 1. The algorithm of Monte Carlo simulation.

4 LEVEL CROSSINGS IN MOROCCO

Level crossings are crossings at the level of a railway with a highway or pedestrian path. They constitute one of the most important sources of accidents in the railway domain in Morocco.

4.1 Description of the System

The Moroccan railway signalling system consists of three parts (**figure 2**):

- Rail part: it consists of a material part (train and rail-road) and of a human part (the operator of the train).
- Road part: it contains a material part (vehicle and road) and a human part (the driver of the vehicle).
- Level crossing: it consists of three main parts:

-Power network and communication network between the components of the railway signalling system.

- Control part: it consists of Programmable Logic Controller and its program.

- Operative part: it consists of sensors (Sensor Ad and Sensor Surrender) and actuators (the road lights, the alarms and the barriers).

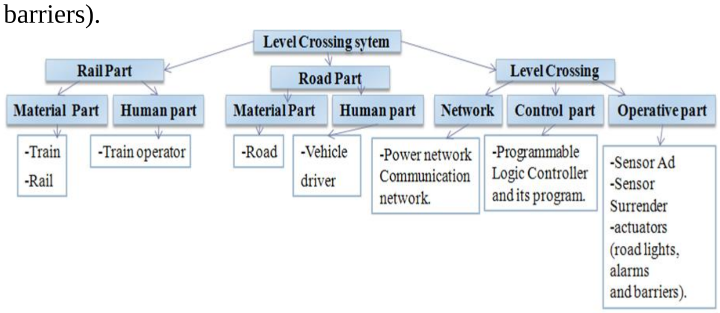

Figure 2. Moroccan level crossing components

4.2 Principle of functionning

The principle of security of the automated level crossing is as follows [13], (**figure 3**):

-Rest situation (Level crossing open): the road fires and the bell switched off, and barriers lifted.

-Activation of the system: a device of detection (pedal of announcement) is placed at a distance of the level crossing, when the train attacks this device, the road fires ignite in red and the bell rings (announcement of the train).

-Closure of barriers: after approximately 7 seconds of the release of the announcement, the barriers begin to fall. The low position of the barriers is reached after 10 seconds.

-Reopening of the level crossing: when the train arrives at the level crossing (35 seconds after the announcement), it attacks the device of rearmament (pedal of surrender). After the complete release of the train, the barriers go up, the road fires and the bell stop ringing.

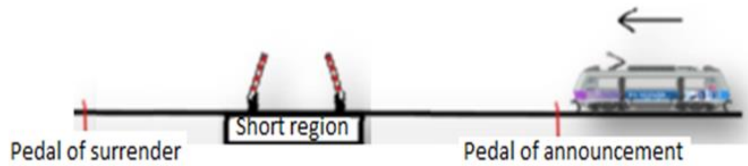

Figure 3. Principle of functioning of the automated level crossing

5 MODEL OF THE LEVEL CROSSING

5.1 Human Factor

The human error can be defined as a fault of the operator, which leads to an accident or a railway incident. In the literature, several works taking into account human factors were proposed. In **[14],** the human reliability is defined as the probability that a task or a work is successfully achieved by a person at a required time if a temporal requirement is necessary.

In fact, the human factor is very difficult to quantify, because of the complexity of the human being, the lack of data and the dependency between the human error and culture and society which are different from a country to another.

In our study, we use the methodology presented in **[15]** to compute the faillure rate of the operator which we suppose that is constant.

The distribution appropriate for the model of rate constant is the exponential distribution. Thus, the rate of transition of the state of functioning to the state of failure is $\lambda_{HF}.\Delta t.$

To obtain a significant value of the faillure rate, we considered the statistics of **118** accidents presented in **[16]** in Morocco from 2000 until 2008.

The safety experts at the National Office of the Moroccan Railroad confirmed that between 80% and 90% of railway accidents are caused by human error. Thus the faillure rate of the operator on every line is:

$$\lambda_{HF}min = \frac{a.p}{y.r} = \frac{118*0.8}{9years*10} = 1.197 * 10^{-4}\ h^{-1} \quad (2)$$

$$\lambda_{HF}max = \frac{a.p}{y.r} = \frac{118*0.9}{9years*10} = 1.347 * 10^{-4}\ h^{-1} \quad (3)$$

Where:

a: number of accidents.

p: human error percentage

y: number of years

r: number of railway

5.2 Reliability bloc diagram of the Moroccan Level Crossing

From the description of the railway signalling system, we model the reliability bloc diagram of the Moroccan Level Crossing.

The meaning of the basic components is given in the **Table 1**.

It is a model composed of 18 elements, the components relating to the three actuators (alarms, road lights and barriers) are modeled in parallel and the other components are in series.

The redundancy in this system is due to the fact that the functioning of one of the three actuators can warn the motorist either by triggering alarms or by lighting road lights or by closing the barriers. The other elements are all necessary for the proper functioning of the system.

Table 1. Failure Rates of Components

Symbol	Meaning	Failure Rates min and max : λ (h-1)
HF	Human Failure	[1,20E-04,1,35E-04]
VF	Vehicle Failure	[1,00E-03, 1,80E-02]
RF	Rail Failure	[1,90E-06, 2,85E-06]
PLCF	Programmable Logic Controller Failure	[4,00E-06, 2,30E-05]
PE	Program Error	[2,50E-09, 5,00E-08]
NCF	Network Communication Failure	[1,00E-07, 5,00E-06]
PNF	Power Network Failure	[1,00E-07, 5,00E-06]
SAF	Sensor Ad Failure	[1,00E-04, 4,00E-04]
SSF	Sensor Surrender Failure	[1,00E-04, 4,00E-04]
AF	Alarm Failure	[1,00E-04, 8,00E-04]
LF	Light Failure	[1,00E-04, 8,00E-04]
MF	Motor Failure	[5,70E-07, 4,50E-06]
TSF	Transmission System Failure	[4,00E-05, 6,00E-05]

We suppose that the reliability of each component follows exponential law with an imprecise failure rates. Thus, the reliability of each basic component i at time t is given by $R_i(t)=\exp(-\lambda_i.t)$.
Note that in this study, since the components are not repairable, the system availability is equal to its reliability.
The reliability bloc diagram of the Moroccan Level Crossing is given in **figure 4.**

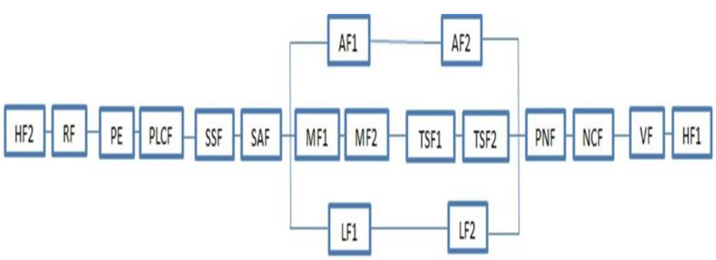

Figure 4. Reliability bloc diagram of the Moroccan Level Crossing

6 RESULTS AND DISCUSSIONS

6.1 Simulation stopping criteria

To identify the influence of the number of simulations to the reliability results of our Level Crossing system, we compute the minimal and the maximal values of the reliability Rmin and Rmax as a function of the number of simulations Ns at the same time t=100h.
So, we take the interval [1000, 100000] of the number of simulations with a step ΔNs=5000, and we plot the functions Rmin=f(Ns) and Rmax=f(Ns) (**figure 5 and 6**).

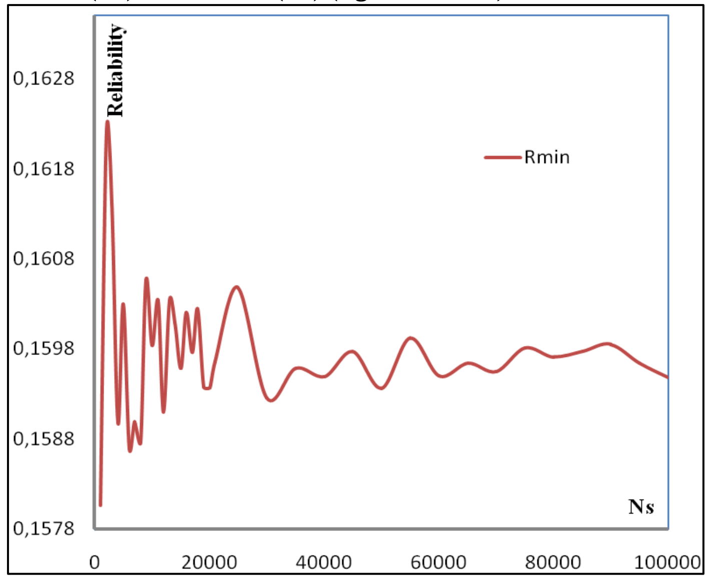

Figure 5. **The minimal Reliability of the Moroccan level Crossing as a function of the number of simulations**

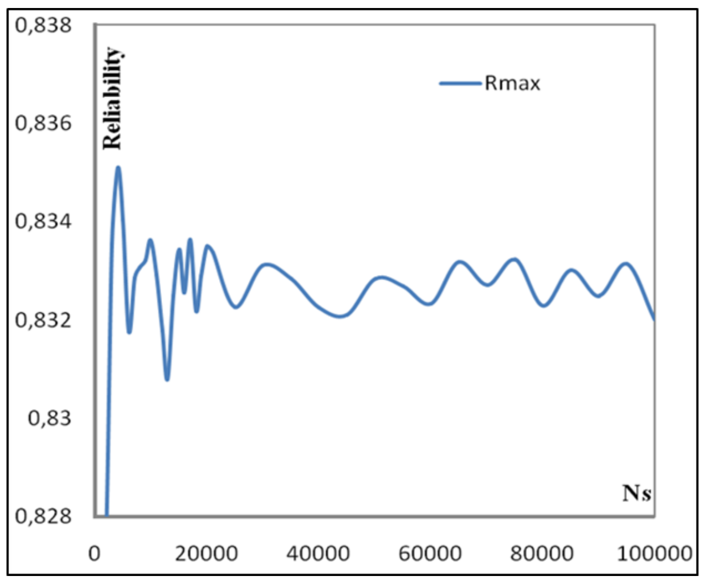

Figure 6. **The maximal Reliability of the Moroccan level Crossing as a function of the number of simulations**

As we can show, the reliability Rmin and Rmax varies depending on the number of simulations, the Rmin varies around the value Rmin(moy)=0.1596 and the Rmax around the value Rmax(moy)=0.8325.
The period variation of the reliability increases and the amplitude variation decreases according to the number of simulations, therefore the reliability will tend towards a constant value when Ns becomes larger.
The optimal number of simulation depends on the desired precision p for each application domain, so the optimal number

of simulation is achieved when the difference between the value of reliability R (Ns1) and R (Ns2) becomes less than or equal to p.
In our case, we desire a precision of the order of 10-3, thus the optimal number of the simulation is achieved when the difference between the value of the reliability R (Ns1) and R (Ns2) is less than or equal to $\mathbf{p=10^{-3}}$, this is verified when the number of simulation is Ns=10000 (figure 7 and 8), so it is unnecessary to increase the number of simulation, for this reason, we will fix Ns = 10000 to continue the work.

6.2 Upper and lower reliability

To evaluate the reliability of the railway signalling system, we plot the result presented in the **table 2** as upper and lower reliability of the Moroccan Level Crossing as a function of time in the interval [0,4000 h].(**figure 7**).

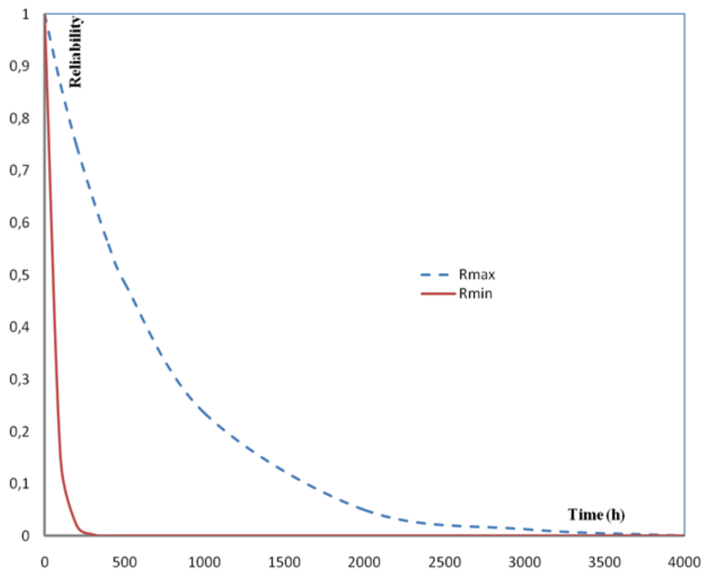

Figure 7. Upper and lower reliability of the Moroccan level Crossing

As we can see, the level crossing system becomes unreliable at time t=400 h and t=4000 h (functionning time of the system) respectively for the minimal and the maximal value of the system reliability. This is due to the fact that no maintenance policies are done on the system in this study.
For example, we consider a Level Crossing at the line FEZ-SIDI KACEM with a density of 42 trains by day, we suppose that for each train the Level Crossing is busy for 2 min, so 84 min=1.4 h of functionning by day with a rate of occupation of RO=1.4/24=5.83%.The Level Crossing in this line becomes unreliable at t=400/1.4=285.714day and t=4000/1.4=2857.142 day respectively for the minimal and the maximal value of the system reliability.
The area between the two curves represents the possible values of the reliability of the system; it is due to epistemic uncertainties of failure rates of basic components. The optimal curve of the reliability depends on the degree of risk to be taken by the decision maker at the National Office of the Moroccan Railroad (ONCF).

6.3 Level Crossing Reliability Distribution

According to the algorithm described above, we save the results in **table 2** for 99 percentile. Then, we have plot a 3D surface showing the distribution of the reliability of the level crossing over the time and the reliability in the interval of time [0,1000h] by using the the parametrs of normal distribution μ and σ (**figure 8**).
The maximum height of the 3D surface that represents the reliability value the more probable varies depending on the width of epistemic uncertainty (Rmax-Rmin); when this latter becomes important, the more probable value of reliability becomes low and vice versa.

Table 2. Results of the Monte Carlo simulation of the Moroccan level crossing

Time (h)	Reliability	μ	σ
10	[0.83,0.981]	0.905	0.044
50	[0.396,0.909]	0.653	0.151
100	[0.158,0.832]	0.494	0.198
200	[0.03,0.701]	0.363	0.195
300	[0.009,0.591]	0.296	0.17
400	[0.006,0.503]	0.24	0.143
500	[0.004,0.427]	0.205	0.12
600	[0.003,0.361]	0.173	0.1
700	[0.003,0.304]	0.143	0.083
800	[0.002,0.26]	0.12	0.071
900	[0.002,0.222]	0.1	0.059
1000	[0.001,0.188]	0.084	0.049
2000	[0.00028,0.03683]	0.014	0.089
3000	[0.00004,0.0728]	0.024	0.017
4000	[0.00001,0.00145]	4.22e-4	3.26e-4

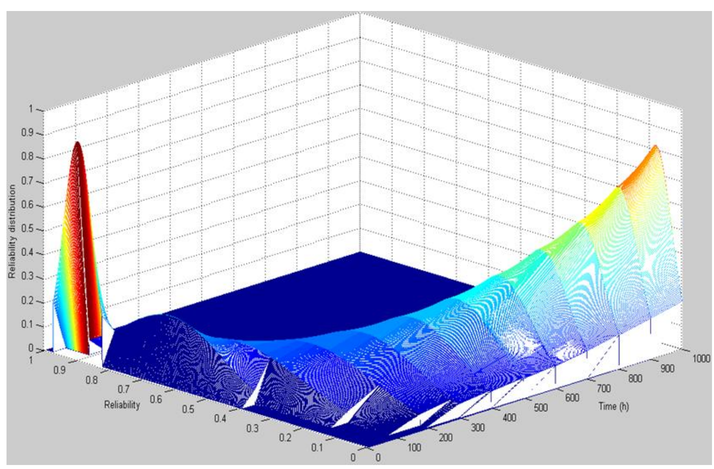

Figure 8. Reliability distribution of the Moroccan level Crossing

The curve which goes through the head of the 3D surface represents the most probable reliability of the Moroccan Level Crossing, and when we move away from the head of the curve the Reliability values becomes less probable, therefore, the

optimal value for this problem depends on the degree of risk to be taken by the decision maker by taking into account the cost of achieving this value of reliability when developing plans for preventive maintenance for example..
For example for t=100 h the distribution of the imprecise reliability is given in **figure 9,** that means that the reliability of the system at t = 100 h is between about 0.2 and 0.8.

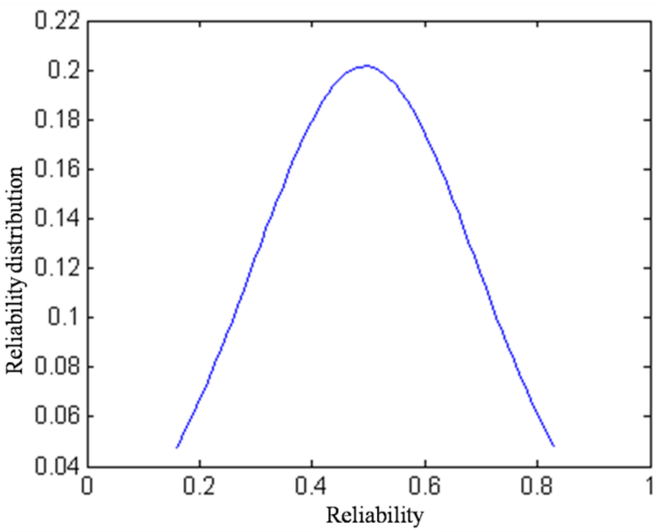

Figure 9. Distribution of the reliability at t=100 h

7 CONCLUSION

In this paper, we have proposed the Monte Carlo simulation to evaluate the reliability distribution of the Moroccan Level Crossing. We have also identified the influence of the number of simulations to the level crossing reliability result as well as the stopping simulation condition. The added value of this approach is the integration of human factor and failures data uncertainty (aleatory and epistemic uncertainty) in the 3D quantitative analysis of the reliability distribution over the time and the reliability values as well as the determination of the influence of the number of simulation to the result. However, this approach does not process model uncertainty.
In our future works, we will complete our study, by considering the imprecision in the quantification of dependency failures between components. We will also study the application of the second-order Monte Carlo simulation when considering components with multi-state systems.

ACKNOWLEDGMENT

In the terms of this paper, we thank the National Office of the Moroccan Railroad (ONCF) as well as the Laboratory of Mechanics, Mechatronics and Control (L2MC) of ENSAM MEKNES and Heudiasyc Laboratory of Compiegne University of Technology. Many thanks go to our colleagues and experts for the source of information and advices they gave us. We also thank obviously the steering committee of this conference, to accept to evaluate our research.

REFERENCES

[1] Paul M, S., Michael G, L., Kristie L, Y., & Guy H, W. (2013). An on-road network analysis-based approach to studying driver situation awareness at rail level crossings. Accident Analysis and Prevention 58, 195-205.

[2] Joe, S., & Clive , R. (2010). Using functional analysis to determine the requirements for changes to critical systems: Railway level crossing case study. Reliability Engineering and System Safety 95, 216-225.

[3] Samantha G, C., Nanyan, Z., & Mohd, R. (2014). Highway-rail grade crossing safety challenges for shared operations of high-speed passenger and heavy freight rail in the U.S. Safety Science 68, 128-137.

[4] Bahloul, K., Defossez, F., Ghazel , m., & Simon, C.-d. (2012). Adding technological solutions for safety improvement at level crossings : a functional specification. Procedia - Social and Behavioral Sciences , 1375-1384.

[5] M.EASA, S. (1994). Reliability-Based design of sight distance at railroad grade crossings. Transp.Res.-A.vol.28 A, No.1. , 1-15.

[6] Rizati, H., Siti, Z. I., & b, I. R. (2014). Pedestrian Crossing Scenario Model Using Petri Nets. Procedia - Social and Behavioral Sciences 129, 406 – 413.

[7] Collart, D. S., Defossez, F., & Bon, P. (2006). Safety requirements and p-time petri nets: A level crossing case study. IMACS Multiconference on "Computational Engineering in Systems Applications"(CESA). Beijing, China.

[8] Ghazel, M. (2009). Using Stochastic Petri Nets for Level-Crossing Collision Risk. IEEE Transactions On Intelligent Transportation Systems, , Vol. 10, No. 4,.

[9] Wullems, C. (2011). Towards the adoption of low-cost rail level crossing warning devices in regional areas of Australia : A review of current technologies and reliability issues. Safety science 49, 1059-1073.

[10] Bohus Leitner (2017) A General Model for Railway Systems Risk Assessment with the Use of Railway Accident Scenarios Analysis, Procedia Engineering 187, 150-159.

[11] Liang, C. et al, (2018). Developing accident prediction model for railway level crossings. Safety Science 101, 48–59.

[12] Grégoire S. Larue et al, (2018). The road user, the pedestrian, and me: Investigating the interactions, errors and escalating risks of users of fully protected level crossings. Safety Science

[13] ONCF. (2013). Sécurisation de la traversée des voies ferrées

au droit des passages à niveau: équipement des passages a niveau non gardés par système automatique d'annonce et de protection. fiche projet, Rabat.

[14] LABADI, Karim. "Contribution à la modélisation et à l'analyse de performances des systèmes logistiques à l'aide d'un nouveau modèle de réseaux de pétri stochastique," Université de Technologie de Troyes (UTT), thèse de doctorat 2005.

[15] Boudnaya, J., Mkhida, A., & Sallak, M. (2014). A dependability analysis of a Moroccan level crossing based on Fault tree analysis and importance measures, MOSIM, NANCY, France.

[16] Bouchiba, (2013), Evaluation de dysfonctionnement d'un système par approche Bayésien: cas du système ferroviaire," Ecole doctorale d'ANGERS, Ecole doctorale de l'EMI, thèse de doctorat.