Dependability analysis of Level Crossing Systems using a fuzzy dynamic fault tree approach

Jaouad BOUDNAYA[a]&Mohamed SALLAK[b]&Abdelhak MKHIDA[a]

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

[a]Moulay Ismail University, ENSAM Meknes, Laboratory of Mechanics, Mechatronics and Control (L2MC), Marjane 2, PO Box 15290, Al-Mansour Road Agouray, 50500 Meknes, Morocco.

[b]Sorbonnes universités, Université de Technologie de Compiègne, Heudiasyc laboratory CNRS UMR 7253, Research Center of Royallieu, 60200 Compiegne, France.

EXTENDED ABSTRACT

Level crossing systems constitute one of the most important sources of accidents in the railroad domain. For this reason, several national offices of railroads launched programs which aim at improving safety of an important number of level crossings because of their dangerousness.

The work presented here deals with modelling the level crossings in order to evaluate their dependability attributes. More specifically, we propose the modelling of the dynamic aspect of level crossing systems using a dynamic fuzzy fault tree approach, and the integration of human factors and components failure data uncertainties in this study.

Indeed, Dynamic Fault Tree (DFT) is an adequate methodology for modelling dynamic systems which involve complicated dynamic characteristics such as sequence and functional dependencies. DFT can be considered as an extension of the standard fault trees by allowing the modelling of complex system components' behaviours and interactions. Unfortunately, a number of issues still remain when using such approaches. One of these issues is handling uncertainties due to limited data available for components of level crossing systems. That's why we associate a fuzzy set approach with DFT.

The proposed method allows the evaluation of the performance of a level crossings system in terms of reliability, and the computation of fuzzy imprecision and importance measures of system components.

The novelty of this paper lies in the combination of DFT with fuzzy set approaches, and the application of the proposed methodology on a real Moroccan level crossing system in order to take into account functional dependency between components failure. Human errors and failure data uncertainties (aleatory and epistemic uncertainties) are also taken into account.

Our final aim is to help engineers and researchers to fulfil some requirements related to safety of level crossing systems by estimating the imprecise reliability of those systems, and identifying the critical components in terms of reliability and uncertainty.

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ABSTRACT: The Level Crossing systems constitute one of the most important sources of accidents in the railroad domain. This work proposes a dependability study of a Level Crossing system using a Fuzzy Dynamic Fault Tree. Particularly, we will show how to evaluate the imprecise failure probability of the Level Crossing systems when considering human errors and failure data uncertainties. Finally, fuzzy importance measures are proposed to identify critical components, and to quantify the influence of data imprecision on the overall system unreliability.

Keywords—Level Crossing systems; Dynamic Fault Tree (DFT); Human Factor; Fuzzy Numbers; Uncertainty.

1 INTRODUCTION

The dependability assessment of level crossing systems is one of the most complex problems which are necessary to approach in order to ensure their safety. Several works related to this problem were presented in the literature. In **(Paul M, Michael G, Kristie L, & Guy H, 2013)**, the authors examined 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 behaviour applications. In **(Joe & Clive , 2010),** the authors analysed the functional interactions between the existing level crossing functions and new technological systems in terms of reliability in order to upgrade and improve the existing systems reliability. The study presented in **(Samantha G, Nanyan, & Mohd , 2014)** showed 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 has identified 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 **(Bahloul, Defossez, Ghazel , & Simon, 2012)** was to improve safety of level crossing by analysing accident/incident data bases and integrating human behaviour 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. In **(M.EASA, 1994)**, the authors presented a probabilistic method that accounted for the variations of the component design variables of sight distance at level crossings when computing system reliability. The method was validated using a Monte-Carlo simulation approach and has led to safer operations at railroad grade crossings. The paper **(Rizati , Siti, & b, 2014)** presented an insight view of translating the sequence of event to model pedestrian level crossing scenarios using Petri Nets approach. The developed model provided an understanding of the risky situation when pedestrian and vehicle are interacted at signalized intersections. In **(Collart, Defossez, & Bon, 2006**), level crossings were modelled by p-time Petri Nets in order to satisfy time specifications defined in safety requirements of railway systems. In **(Ghazel, 2009)** the authors proposed a global model of the level crossing implying at the same time the rail and road traffic by using stochastic Petri Nets. This model was obtained by a progressive integration of the developed elementary models; each of them described the behaviour of a section. It allowed the follow-up and the qualitative and quantitative evaluation of the effect of various factors on the level of the risk.

In this paper, we propose the evaluation of the imprecise occurrence probability of the Feared Event (collision between a train and a vehicle) of a Level Crossing system using Fuzzy Dynamic Fault Tree (FDFT), as well as the determination of the critical components in terms of reliability and imprecision.

2 DESCRIPTION AND ARCHITECTURE OF LEVEL CROSSING SYSTEMS

In this section, the description and architecture of level crossings are based on level crossing systems used in Morocco which are similar to those used in other countries.

2.1 Definitions and types of level crossings

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. This led early in the railway to choose a radical solution: temporarily prohibiting the road crossing, often physically by barriers. These barriers can be operated manually or automatically.

We can classify crossings into two main categories:

-Level Crossings with manual barrier:

The guarded level crossings are managed by guards. They must ensure their safety, either by closing the barriers from the approach of a train or stopping trains in case of problems in the level, this type of level crossing has a tendency to disappear.

-The automated level crossings:

The principle of safety of the level crossing not guarded presented in **figure 1** is as follows **(ONCF, 2013)**:

-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 there lease 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.

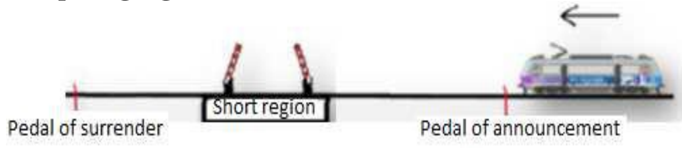


Figure 1. Principle of functioning of the automated level crossing.

2.2 Prototype of the Moroccan Level Crossing

Within the framework of the global program of the safety of the level crossing of the Moroccan railway, it was decided in July, 2012 to strengthen the safety of the level crossings not guarded and situated on lines with high traffic (approximately 260 level crossings) by a program that extends through 2015.

New equipments will be installed on the unguarded level crossing and will allow announcing to the road users the approach of the train. For instance, **Figure 2** represents the first prototype which is put in the level crossing N_3080 situated at km 168+088 between Tangier and Sidi Kacem, on May 7th2013 by a Spanish company **(ONCF, 2013)**.

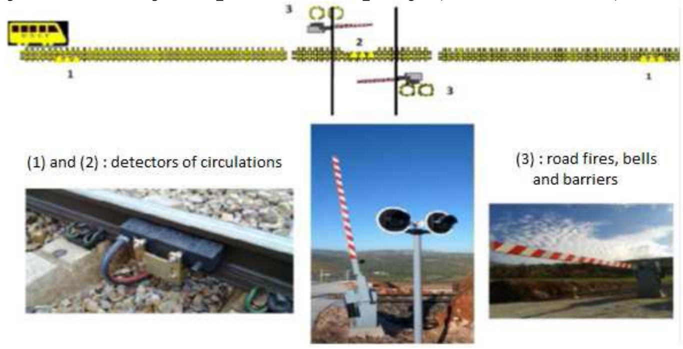


Figure 2. Prototype of the Moroccan Level crossing.

3 DYNAMIC FAULT TREE ANALYSIS

The traditional FTA is not well adapted to model the dependencies between components failure. To overcome this difficulty, **Dugan et al**. proposed a new method called Dynamic Fault Tree (DFT) by introducing dynamic gates to describe the dynamic behaviours of these systems **(Dugan, Bavuso, & Boyd, 1992)**. There are four major basic dynamic gates which are presented in the **figure 3**: the priority AND (PAND), the sequence enforcing (SEQ), the warm SPARE, and the functional dependency (FDEP).

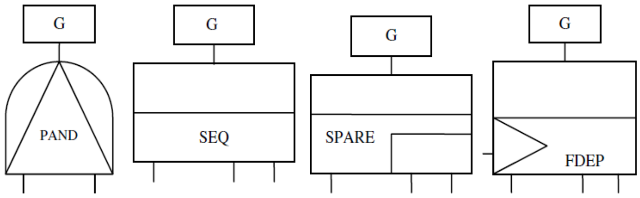


Figure 3. The basic dynamic gates

In our paper, we will use the FDEP gate. In this gate, there will be one trigger input (either a basic event or the output of another gate in the tree) and one or more dependent events. The dependent events are functionally dependent on the trigger event. When the trigger event occurs, the dependent basic events are forced to occur. The truth table of the FDEP gate with a trigger input and two dependent events is given in **the table 1**.

Table 1. The truth table of the FDEP gate

Trigger T	Dependent event A	Dependent event B	Output
1	1	1	1
0	1/0	1/0	0

In the Markov chain generation (**figure 4**), when a state is generated in which the trigger event is satisfied, all the associated dependent events are marked as having occurred. The separate occurrence of any of the dependent basic events has no effect on the trigger event.

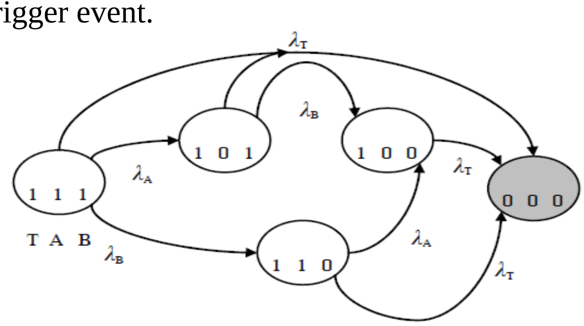


Figure 4. Markov model for FDEP gate

4 THE PROPOSED FUZZY DYNAMIC FAULT TREE APPROACH

4.1 *Fuzzy numbers*

The fuzzy set theory was introduced by Zadeh **(Zadeh, 1978)**. It can deal with fuzzy characteristics of uncertainty (aleatory and epistemic) in real engineering systems.

Given a universal set *U*, for a set *A* and for each element *u* of *U*, there exists a real number $\mu_A(u) \in [0,1]$ that corresponds to *u*, which represents the degree of *u* belonging to *A*. We call the set *A* a fuzzy set, and the value $\mu_A(u)$ the membership degree of *u* to *A*.

$$\mu_A : U \longrightarrow [0,1]$$
$$u \mid\longrightarrow \mu_A(u)$$

A fuzzy set *A* is called a fuzzy number if it is a normal and a convex fuzzy set.

In our paper we use triangular fuzzy numbers *A(a,b,c)* (Note that the proposed approach can be easily extended to other fuzzy numbers: trapezoidal, …), which are defined by their membership functions as follows:

$$\mu_A = \begin{cases} \frac{x-a}{b-a}, a \le x < b \\ 1, x = b \\ \frac{x-c}{b-c}, b < x \le c \\ 0, otherwise \end{cases}$$

4.2 *Fuzzy dynamic fault tree*

The Fuzzy Dynamic Fault Tree (FDFT) is a methodology for reliability evaluation and analysis of systems having dynamic characteristics and fuzzy uncertainty. It is a combination of Markov model and Fuzzy set theory **(Li, Huang, Liu, Xiao, & Li, 2012)**.

This methodology is based on the transformation from the DFT into the Fuzzy Markov Model with *n* states s_i ($1 \le i \le n$) having fuzzy state transition rate λ_{ij}.

The Fuzzy Markov Model (state transition diagram) is obtained by analyzing the truth table of the Dynamic Fault Tree in order to identify the number of states of the system including the initial state, the degraded states and the failed state. So, the system has *n* states: initial state S_1, *n-2* degraded states, and failure state S_n.

Then the fuzzy state transition rate matrix is given as follows:

$$Q = (\lambda_{ij}) = \begin{pmatrix} \lambda_{11} & \dots & \lambda_{1n} \\ \dots & \dots & \dots \\ \lambda_{n1} & \dots & \lambda_{nn} \end{pmatrix}$$

As a result, the differential equations with the fuzzy transition rate take the form of:

$$\left[\frac{dP(t)}{dt}\right]^T = P(t).Q$$

To solve the differential equations, we use the Laplace transform with the initial condition: $P_1(0)=1$ and $P_i(0)=0$ $(i \neq 1)$.

After solving the linear equations to obtain $P_n(s)$, we use the inverse Laplace transform to find $P_n(t)$. Then the membership function of fuzzy probability $P_n(t)$ can be calculated at different α-cut levels.

4.3 *Fuzzy dependability importance measures*

In 1969, Birnbaum first introduced the concept of components' reliability importance **(Birnbaum, 1969).**This measure was defined as the probability that a component *i* is critical to system failure.

In our study we consider the fuzzy importance measures as the Euclidian distance between the fuzzy failure rates as follows:

$$I(i)=\sqrt{(P_{a1}-P_{a0})^2+(P_{b1}-P_{b0})^2+(P_{c1}-P_{c0})^2}$$

WhereP_{a1}, P_{b1} and P_{c1} denote respectively the failure probability of the system when it is known that the component *i* is in the working state ($\lambda_a=1$, $\lambda_b=1$and $\lambda_c=1$), and P_{a0}, P_{b0} and P_{c0} denote respectively the failure probability of the system when it is known that the component *i* is in the failed state ($\lambda_a=0$, $\lambda_b=0$and $\lambda_c=0$).

4.4 *Fuzzy uncertainty measures*

The epistemic uncertainties (imprecision) can be reduced by increasing the amount of information, it is then important to be able to identify the more imprecise components.

In this study we consider the fuzzy imprecision measures as the Euclidian distance between the fuzzy failure rates as follows:

$$J(i)=\sqrt{(P_a-P_{a'})^2+(P_b-P_{b'})^2+(P_c-P_{c'})^2}$$

Where: P_a, P_b and P_c denote respectively the failure probability of the system when it is known that the component *i* has an imprecise failure rate, and $P_{a'}$, $P_{b'}$ and $P_{c'}$ denote respectively the failure probability of the system when it is known that the component i has a constant failure rate.

5 MODELLING OF THE LEVEL CROSSING

5.1 *Description of the system*

The Moroccan railway signalling system consists of three parts:

* 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 of Ad and Sensor of Surrender) and actuators (the road lights, the alarms and the barriers).

5.2 *Integration of the 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 **(LABADI, 2005)**, 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 our study, we use the methodology presented in **(Boudnaya, Mkhida, & Sallak, 2014)** to compute the rate of error of the operator which we suppose that is constant.

So, we considered the statistics of the Moroccan railway accidents presented in **(ONCF, 2013)** in Morocco from 2000 till 2008 on the 10 busiest lines (see **Table 2)**, and we identify the rate of Human error on every line by the formula:

$$\lambda_{HF}=\frac{a.p}{y.r}$$

Where:

a: number of accidents.

p: human error percentage

y: number of years

r: number of railway

Table 2.Statistics of the railway accidents in Morocco.

Years	**Numbers of accidents**
2000	11
2001	6
2002	18
2003	13
2004	15
2005	21
2006	12
2007	7
2008	15
Total	118

So, the fuzzy Human Failure is obtained by replacing the human error percentage respectively by 80%, 85% and 90%.

Then, the fuzzy Human Failure is as follows: HF=[1.20E-4,1.30E-4,1.35E-4].

5.3 *Model of the system*

From the description of the Moroccan railway signalling system in the previous section, we were able to model the Feared Event (Collision between train and vehicle) by a Dynamic Fault Tree (DFT) shown in **figure 5**.

We suppose that the Motors failure depends on the Transmission System Failure. If the trigger event (Transmission System Failure) occurs, the dependent event (Motor Failure) occurs subsequently, and the output becomes true.

The basic events which produce the feared event are given in the **table 3**.

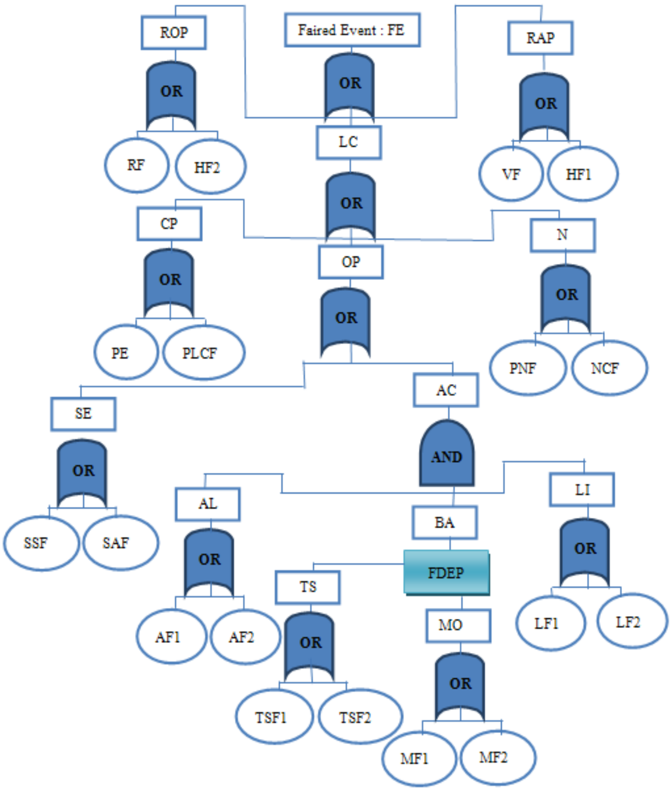


Figure 5. Dynamic Fault Tree of the Moroccan Level Crossing.

Table 3.Fuzzy failure data of Basic Events.

Symbol	Basic Events	Fuzzy Failure Rates : λ (h^{-1})
HF	Human Failure	[1.20E-4,1.30E-4,1.35E-4]
VF	Vehicle Failure	[1.00E-3,1.00E-2,1.80E-2]
RF	Rail Failure	[1.90E-6,2.35E-6,2.85E-6]
PLCF	Programmable Log ic Controller Failure	[4.00E-6,1.35E-5,2.30E-5]
PE	Program Error	[2.50E-9,2.65E-8,5.00E-8]
NCF	Network Communication Failure	[1.00E-7,2.50E-6,5.00E-6]
PNF	Power Network Failure	[1.00E-7,2.50E-6,5.00E-6]
SAF	Sensor Ad Failure	[1.00E-4,2.00E-4,4.00E-4]
SSF	Sensor Surrender Failure	[1.00E-4,2.00E-4,4.00E-4]
AF	Alarm Failure	[1.00E-4,4.00E-4,8.00E-4]
LF	Light Failure	[1.00E-4,4.00E-4,8.00E-4]
MF	Motor Failure	[5.70E-7,3.00E-6,4.50E-6]
TSF	Transmission System Failure	[4.00E-5,5.00E-5,6.00E-5]

We suppose that these events follow exponential laws with an imprecise failure rates represented by a fuzzy triangular numbers given in the same **table 3**.

The symbols of intermediate events of the fault tree are given in **table 4.**

Table 4.Symbol of Intermediate Events

Symbol	Intermediate Event
FE	Feared Event
ROP	Road Part
RAP	Rail Part
LC	Level Crossing
N	Network
CP	Control Part
OP	Operative Part
SE	Sensors
AC	Actuators
BA	Barriers
AL	Alarms
LI	Lights
M	Motors
TS	Transmission Systems

6 RESULTS AND DISCUSSIONS

According to the DFT shown in **figure 5** and the basic failure data shown in **Table 3**, the failure probability of the Moroccan Level Crossing system is analysed based on FDFT. The simplified DFT shown in **Figure 6** is transformed into the fuzzy Markov model represented in **figure 7** by analyzing its truth table to identify the states of the system.

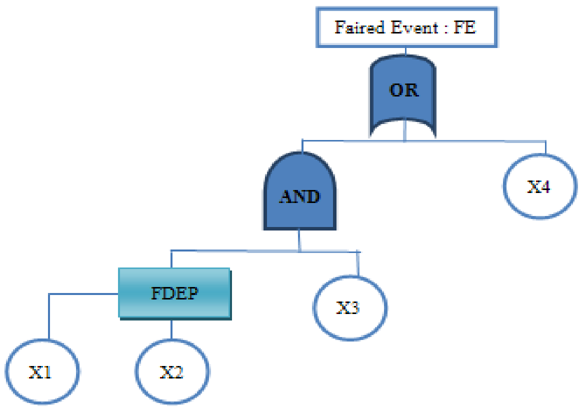


Figure 6.Simplified Dynamic Fault Tree of the Moroccan Level Crossing.

The events Xi (i=1, 2, 3, 4) are combinations of serial or parallel events as follows:

X1=TSF1+TSF2
X2=MF1+MF2
X3= (LF1+LF2).(AF1+AF2)
X4=HF2+RF+PE+PLCF+SSF+SAF+PNF+NCF +VF+HF1

The failure rates of systems composed of serial components are calculated as follows:

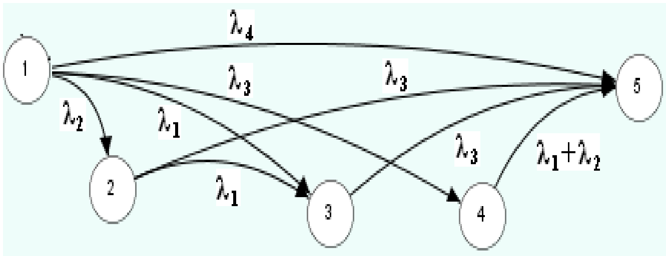
$\lambda_1 = \lambda_{TSF1} + \lambda_{TSF2}$

$\lambda_2 = \lambda_{MF1} + \lambda_{MF2}$

$\lambda_4 = \lambda_{HF2} + \lambda_{RF} + \lambda_{PE} + \lambda_{PLCF} + \lambda_{SSF} + \lambda_{SAF} + \lambda_{PNF} + \lambda_{NCF} + \lambda_{VF} + \lambda_{HF1}$

On the other hand, we suppose that the failure rate of two parallel components is constant and the components are not repairable, so it is equal to the reciprocal of the MTTF (Mean Time to Failure) of

$$\lambda_3 = \left(\frac{1}{\lambda_{LF1} + \lambda_{LF2}} + \frac{1}{\lambda_{AF1} + \lambda_{AF2}} - \frac{1}{\lambda_{LF1} + \lambda_{LF2} + \lambda_{MF1} + \lambda_{MF2}} \right)^{-1}$$



the system as follows:

Figure 7.State transition diagram of the Moroccan Level Crossing.

The fuzzy Markov model shows the five possible states of the system, so the occurrence probability of the Feared Event is represented by the 5th state.

Then we developed the system of linear differential equations as follows:

$$\left[\frac{dP(t)}{dt} \right]^T = P(t).Q$$

With:

$$Q = \begin{pmatrix} -\sum_{i=1}^{4} \lambda_i & \lambda_2 & \lambda_1 & \lambda_3 & \lambda_4 \\ 0 & -(\lambda_1 + \lambda_3) & \lambda_1 & 0 & \lambda_3 \\ 0 & 0 & -\lambda_3 & 0 & \lambda_3 \\ 0 & 0 & 0 & -(\lambda_1 + \lambda_2) & \lambda_1 + \lambda_2 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\frac{dP(t)}{dt} = \begin{pmatrix} \frac{dP_1(t)}{dt} \\ \frac{dP_2(t)}{dt} \\ \frac{dP_3(t)}{dt} \\ \frac{dP_4(t)}{dt} \\ \frac{dP_5(t)}{dt} \end{pmatrix} \qquad P(t) = \begin{pmatrix} P_1(t) \\ P_2(t) \\ P_3(t) \\ P_4(t) \\ P_5(t) \end{pmatrix}$$

To solve the system of differential equations, we used the Laplace transform with the initial condition: $P_1(0)=1$ and $P_i(0)=0$ (i=2,3,4,5), we then have to solve : $A.L(s) = B$

With:

$$L(s) = \begin{pmatrix} L_1(s) \\ L_2(s) \\ L_3(s) \\ L_4(s) \\ L_5(s) \end{pmatrix} \qquad B = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$A = \begin{pmatrix} s + \sum_{i=1}^{4} \lambda_i & 0 & 0 & 0 & 0 \\ -\lambda_2 & (s + \lambda_1 + \lambda_3) & 0 & 0 & 0 \\ -\lambda_1 & -\lambda_1 & s + \lambda_3 & 0 & 0 \\ -\lambda_3 & 0 & 0 & (s + \lambda_1 + \lambda_2) & 0 \\ -\lambda_4 & -\lambda_3 & -\lambda_3 & -(\lambda_1 + \lambda_2) & s \end{pmatrix}$$

After simplification of the solution using the decomposition in simple element we find:

$$L_5(s) = \frac{a}{s} + \frac{b}{s+e} + \frac{c}{s+f} + \frac{d}{s+g}$$

With:

$$a = 1$$

$$b = \frac{-\lambda_3}{\lambda_3 + \lambda_4}$$

$$c = \frac{-(\lambda_1 + \lambda_2)}{\lambda_1 + \lambda_2 + \lambda_4}$$

$$d = \frac{(\lambda_1.\lambda_3 + \lambda_2.\lambda_3 - \lambda_4{}^2)}{(\lambda_3 + \lambda_4).(\lambda_1 + \lambda_2 + \lambda_4)}$$

$$e = \lambda_1 + \lambda_2$$

$$f = \lambda_3$$

$$g = \sum_{i=1}^{4} \lambda_i$$

To find the occurrence probability of the Feared Event over the time, we used the usual inverse Laplace transforms, so the solution becomes:

$$P_5(t) = a + b.\exp(-e.t) + c.\exp(-f.t) + d.\exp(-g.t)$$

The coefficients a, b, c, d, e, f and g are triangular fuzzy numbers which are combinations of the failure rates presented in the **table 3**.

The membership of fuzzy failure probability of the Level Crossing system at different α-cut levels is represented in **Figure 8** at time *t=100h*.

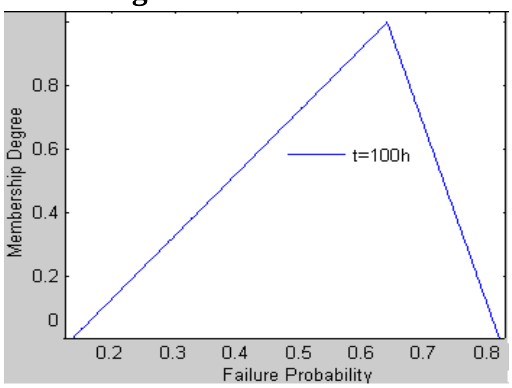
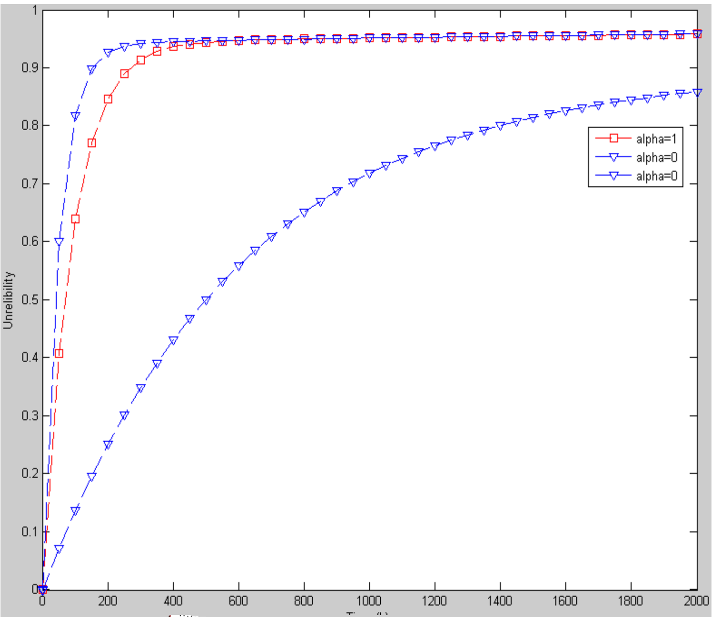


Figure 8. The membership function of P_5 at t =*100h*.

The median value of fuzzy failure probability is 0.638 at time t=100 hours.

The unreliability curves over the time (the occurrence probability of the Feared Event) presented in **Figure 9** are obtained by the fuzzy failure rates corresponding to $\alpha=0$ and $\alpha=1$. The 3D surface shown in the **Figure 10** presents the membership of fuzzy failure probability of the Level Crossing system over the time and the failure probability.



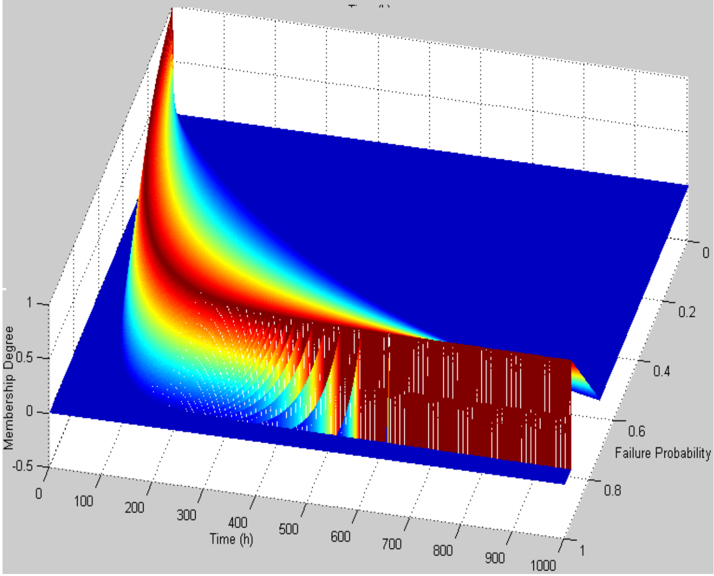


Figure 9.The fuzzy unreliability of the system with α=0 and α=1

Figure 10.The membership of fuzzy failure probability of the system over the time

We have identified the fuzzy importance measures of our system components (see **figure 11**). As we can see the more critical components are VF, MF, and TSF. So, we have to concentrate our efforts on these components in order to increase the overall system reliability.

We also determine the imprecision measures of the Level Crossing elementary components (see **figure 12**). As we can see the more imprecise components are PE, VF and RF. So, we have to concentrate our efforts on collecting more data on these components in order to reduce the imprecision of the overall system reliability.

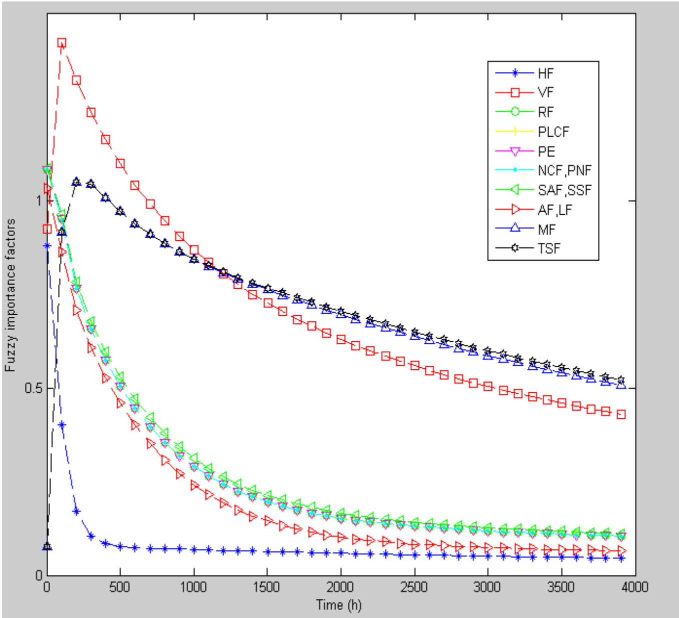


Figure 11.Fuzzy Importance Measures of the level crossing components as a function of time.

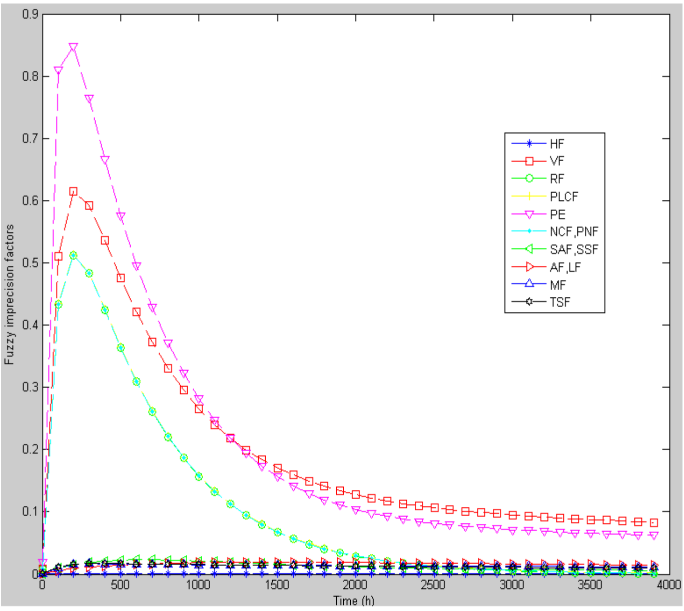


Figure 12.Fuzzy Imprecision Measures of the level crossing components as a function of time

7 CONCLUSION

In this paper, we have proposed an approach based on Fuzzy Dynamic Fault Tree (FDFT) to evaluate the fuzzy unreliability of a Level Crossing. We have also identified the most critical components of this Level Crossing in terms of criticality and uncertainty. It is an original approach for the integration of dependencies between components and the data uncertainty (aleatory and epistemic).

In our future work, we will complete our study by considering multi-state components. Other importance measures to characterize the degree of dependency between components will be also studied.

8 ACKNOWLEDGMENTS

In the terms of this paper, we thank the National Office of the Moroccan Railroad (ONCF) as well as the Center of Doctoral Studies of ENSAM MEKNES, 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 the European Safety and Reliability Conference 2015(ESREL 2015), to allow us to participate in this conference and so to communicate our research and to share our conclusions with colleagues.

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