

Dependability Assessment of the Railway Signalling Systems Based on the Stochastic Petri Nets Analysis

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Abstract: In this article, we propose a methodology to evaluate the performances of the railway signalling systems in terms of the availability. Firstly, level crossings in Morocco are presented. Secondly, a railway signalling system ERTMS level 2 modelling is proposed. The human factor and network failures are also taken into account. Finally, this system performance evaluation is proposed in every state (nominal way of functioning, degraded mode, and failure mode).

Keywords: Railway Signalling System, Level Crossing, Modelling, Petri Nets, Risks, Accident, Availability.

1. Introduction

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

Numerous works with various methods are developed in this sense:

In the article [1], level crossings are modelled by p-time Petri nets to answer certain requirements of safety. The article [2] proposes 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 behaviour of a section. It allows the follow-up, the qualitative and quantitative evaluation of the effect of various factors on the level of the risk. The study reported in [3], presents a new approach of the dependability aiming at the evaluation of a set of hazards likely to be met during the operational life cycle of a system. This new approach is applied to the study of a new European signalling system ERTMS, superimposed on the French lateral signalling by using colored Petri nets. In [4], the modelling of the railway signalling system ERTMS level 2 is made by Statecharts. This work proposes the evaluation of the performances of this system in terms of availability and of mean time spent in every state (nominal way of functioning, degraded mode and failure mode) by integrating human factors as well as network failures.

In this paper we propose a model of the level crossing according to the European standards based on stochastic Petri Nets, by integrating the human behaviour and network failures. Then, we simulate the model by using statistics published by the Federal Railroad Administration in the United States from 2007 till 2011 [5], to evaluate the availability of the railway signalling system.

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2. The Level Crossings in MOROCCO

2.1. Rail network in Morocco

Railway transport is a strategic element in the development of the Moroccan economy. This justifies the necessity to develop adequate infrastructure, enabling the sector to play its role in providing a service increasingly perform ensuring the necessary security for driving under the best conditions.

The Moroccan railway network consists of 2110 km of lines including 600 km of double track (cf. **Figure 1**).

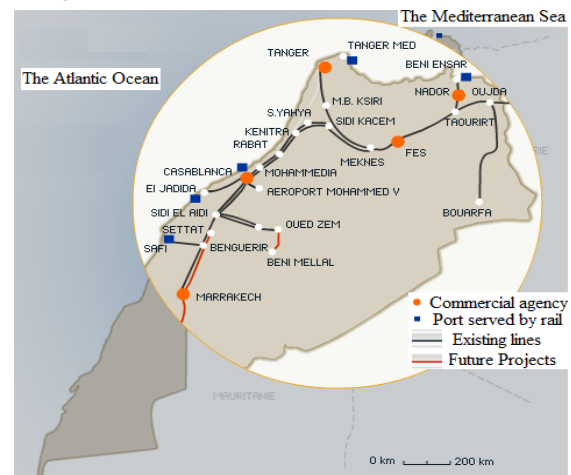


Figure.1 Moroccan railway map

The level crossings

• Definition:

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

• Types of level crossings:

We can easily 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 security of the level crossing not guarded is as follows [6],(cf. **Figure 2**):

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

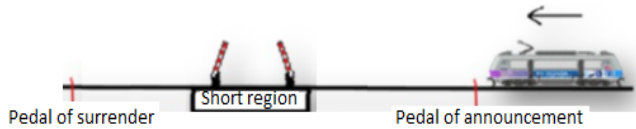


Figure.2Principle of functioning of the automated level crossing

• **Prototype of the Moroccan Level crossing:**

Within the framework of the global program of the security 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 3** 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 7th 2013 by a Spanish company[6].

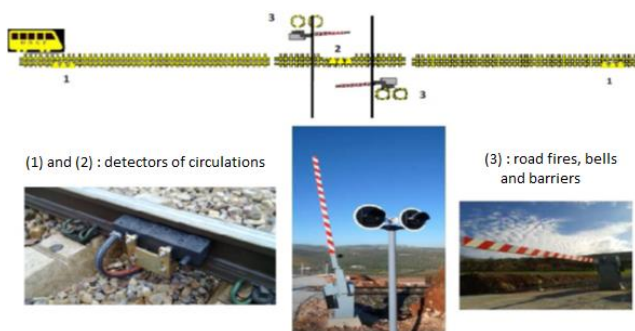


Figure.3Prototype of the Moroccan Level crossing

3. Generalities on the Petri Nets

3.1. Definition

A Petri Net is a quintuple: $PN = (T, P, Has, M 0)$
 T : Set of transitions $T = \{t1, t2, t1\}$
 P : Set of places $P = \{p1, p2, pm\}$
 A : Set of arcs $A = \{a1, a2, an\}$
 $M0$: initial marking: $\{m (pi)\}$ (integer $\geq 0 =$ numbers of tokens

in the place Pi). [7]

Example:

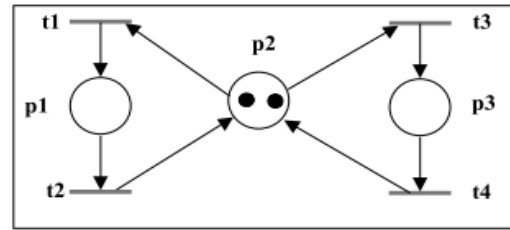


Figure.4Example of a PN

$T = \{t1, t2, t3, t4\}$
 $P = \{p1, p2, p3\}$
 $Arcs = \{(p2, t1), (t1, p1), (p1, t2), (t2, p2), (p2, t3), (t3, p3), (p3, t4), (t4, p2)\}$
 $M0 = [0 \ 2 \ 0]$
 1 2 3

3.2. The Stochastic Petri Nets

An ordinary Stochastic Petri Net in exponential laws $SPN = \langle PN, (\mu 1, \mu 2, \mu q) \rangle$ is an ordinary time Petri Net whose durations of sensitization of every transition Tj are random variables pulled in exponential distributions of parameters $(\mu 1, \mu 2, \mu q)$ [7].

The Stochastic Petri nets were introduced by Guilder since 1978 to answer certain problems of evaluation bound to the safety of the computer systems. These problems are bringing in random phenomena; the transitions of the Petri Net contained random time of crossing, distributed by an exponential law. This exponential distribution allows exploiting the mathematical properties of a process of Markov. Well extended, this concept was widely developed from the beginning of the 80s to fulfil the requirements of the more complex modelling such as the modelling of the systems of production [8].

The basic notions as well as the main properties are found in numerous works [9], [10].

Numerous classes of Stochastic Petri Nets are proposed for the analysis of the performances of the production systems. The characteristics of the various classes of Stochastic Petri nets are essentially situated in the nature of the transitions used. Initially, a Stochastic Petri Net has all its transitions timed by a random time which is distributed with an exponential law, but we find other types of transition. [8]

➤ **Generalized stochastic Petri nets (GSPN)**

The network consists of transition with a no temporization called immediate transition and of transition with a random temporization distributed exponentially said stochastic transitions.

➤ **Deterministic stochastic Petri Nets (DSPN)**

It is an extension of the generalized Stochastic Petri Nets. The network contains immediate transitions (lasted sensitization zero), transitions with deterministic delays (lasted sensitization constant) and transitions with stochastic delays distributed following exponential laws [8].

4. Modelling of the Level Crossing by Petri Net

4.1. Railway signalling system ERTMS

The European system of surveillance of the rail traffic (ERTMS) was introduced to guarantee the interoperability between different

countries and manufacturers by creating a European standard for the systems of control-command of trains.

In this paper, we only consider the ERTMS level 2 which is the most used in Europe whose architecture is represented in **Figure 5**.

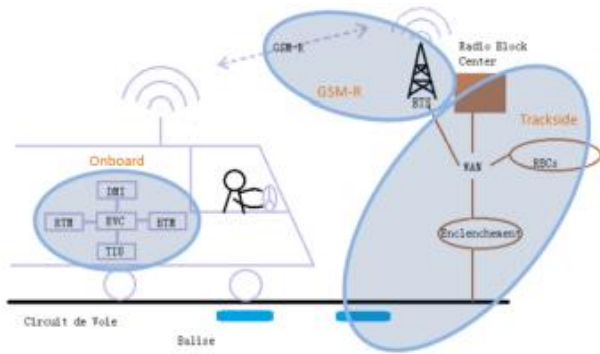


Figure.5Architecture of the ERTMS level 2

It consists of three parts: the “Onboard” system, the “Trackside” system and the “GSM-R” system [4].

➤ **The “Onboard” System:**

It is embarked on the train and serves to control the movements of the train. It receives the information resulting from the “Trackside” system to create a "curve of braking". The train has to respect this profile of speed to slow down or brake before the stop or emergency signs. It also receives messages resulting from beacons and sends data which describe the position of the train and the mode of operation, to the “Trackside” system via the "GSM-R".

If the driver does not succeed in realizing a correct operation in time, the "Onboard" system uses automatically the procedure of braking.

➤ **The “Trackside” system:**

It serves to draw routes, to collect the state of occupation of the way circuit, to detect the position of the train and to send correct profile of speed to the train.

➤ **The “GSM-R” system:**

It is a standard of wireless communication based on the "GSM" for the applications and the railway communication. For the direction "edge to ground", the frequency of the "GSM-R" Messages is situated between 876 MHz and 880 MHz. For the direction "ground to edge", the frequency of the "GSM-R" messages is between 921 MHz and 925 MHz.

This signalling system is considered as “SOS” (System-Of-Systems) which consists of three systems: “Onboard”, “Trackside” and “GSM-R”. Indeed, an “SOS” is a system consisting of independent, autonomous and complex systems which cooperate to reach a common goal [4].

4.2. 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 [11], the human reliability is defined by 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 the literature, numerous models were proposed to estimate and study the human factor, among these models:

➤ **Models stemming from the psychology and from the ergonomics of the work:**

Among these models, the model SRK of Rasmussen, supposes that the cognitive control and the human cognition are made at several levels of abstraction. The highest layers correspond to a more

complex data processing [11].

➤ **Models Stemming from Engineering Sciences**

The method THERP (Technique for Human Error Rate Prediction), which is a method centred on the operator (individual level), is called first generation because of the sequential model of accident on which is based [11].

➤ **Models Stemming from Human and Social Sciences**

By taking for example the method MERMOS which is developed to update the approach of evaluation of the missions of the operators in accidental conduct, the failure of the mission can arise by several independent scenarios of failures (that will be necessary to quantify) [11].

In our study, we suppose that the rate of error of the operator is constant. The distribution appropriate for the model of rate constant is the exponential distribution. Thus, the rate of transition from the state of functioning to the state of failure is $\lambda_{op} \Delta t$. To obtain a significative value of the rate of error, we considered the statistics published by the Federal Railroad Administration in the United States from 2007 till 2011 [5]. Human factor and numbers of corresponding accidents on 107 lines in the United States are given in the **table 1**:

Table 1.Statistics of the accidents bound to human factors

	2011	2010	2009	2008	2007	Total
Absence of the operator	74	63	53	91	101	382
Sleepy operator	3	0	2	3	3	11
Weakening because of medicament / alcohol	0	1	0	0	1	2
Incapacitated because of wound / disease	1	0	0	0	1	2
Physical state of the operator	1	0	0	0	1	2

Thus the rate of error of the operator on every line is:

$$\lambda_{OP} = \frac{382+11+2+2+2}{5years*107} = 8.514*10^{-5} h^{-1} \quad (1)$$

4.3. Integration of the Network Failures

The communication network also is a factor which influences the performance of the “SOS”.

In the literature, several methods of networks reliability analysis were proposed. These methods are mainly based on the simulations of Monte Carlo [12], [13].

In our study, we suppose that the rate of failure of the network is constant. Besides, if the network breaks down, a repair can be made, so the rate of transition from the state of functioning to the State of failure is $\lambda_n \Delta t$, and the rate of transition from the state of failure to the state of functioning is $\mu_r \Delta t$ where $\mu_r = 0.6 h^{-1}$ represent the rate of repair.

To obtain a significant value of the rate of failure of the network, we considered the statistics published by federal Railroad Administration in the United States from 2007 till 2011 [5]. Factors and numbers of corresponding accidents on 107 lines in the United States are given in the table 2:

Table 2.Statistics of the accidents bound to the network failures

	2011	2010	2009	2008	2007	Total
Radio communication, failure to obey	4	5	4	9	9	31
Radio communication, failure of sending / reception	1	2	0	4	4	11
Remote control, loss of communication	1	0	0	1	0	2

According to **table 2**, the rate of failure of the network on every line is calculated as the following way:

$$\lambda_n = \frac{31+11+2}{5 \text{ years} * 10^7} = 9.3885 * 10^{-6} h^{-1} \quad (2)$$

4.4. Modelling under SNOOPY

➤ **Principle of Modelling :**

First, the three systems enter the "Waiting" state. If the variable "Start" is true, all the systems go to the "Normal" state.

At the beginning, the "Onboard" system is in the "Calculation" state, the "Trackside" system is in the "Collection Info Calculation" state and the "GSM-R" system is in the "Collect Message" state.

When an event "Signal From Track " arrives and that the frequency of the " GSM-R " messages is superior to 900 MHZ, the "Trackside" system sends information to the "Onboard" system, then the "Onboard" system goes to the "Receive" state, the "Trackside" system goes to the "Send" state and the "GSM-R" system enters the "Track 2 Train" state.

When an event "End Send To Train" arrives, the "Onboard" system goes into the "Calculation" state, the "Trackside" system goes into the state "Collection Info Calculation" and the "GSM-R" system returns in the "Collect Message" state.

The "Onboard" system has a degraded state. When an operation arrives, if the operator is available, the system enters the "Operation By Operator" state; otherwise, the system enters the "Operation By Computer" state which is a sub-state of the "Degraded Onboard" state. When the event "End Operation" arises, the system enters the "Calculation" state if the operator is not available; otherwise, the "Onboard" system returns to the "Normal" state.

Every system possesses a state of failure. This state of failure is constituted by two types of failures.

The first one is the "Error State Of Net". A variable "network_failed" serves to indicate the network state. It is modelled by a Boolean .When it takes the value "1"; the systems enter the "Error State" state. When this failure is repaired, an event "Repair Net" arrives, the systems enter the "Correct State" state.

The second one is the "Order Of Error of Net". When the controller of the rail traffic notices an anomaly in the network, he can give an instruction "Error Train 2 Track" or "Error Track 2 Train" immediately to interrupt the network and the systems enter the "Order of Error of Net" state.

This failure can be repaired by the events of repair corresponding to "Repair Send _OB ", "Repair Receive _OB", "Repair Send _TS", etc. When the two failures are repaired, the systems can

return in the "Normal" or "Degraded" state. When the variable "End" is true, all the systems return to the "Waiting" State [4].

➤ **Models of the Three Systems :**

We modelled the three components of the railway signalling system: "Onboard", "Trackside" and "GSM-R" by stochastic Petri Nets thanks to the software "SNOOPY" which uses Petri net theory and offers the possibility to construct and analyse models, and to represent their structural and dynamic properties by various techniques. It was dedicated at first to the simulations of the biological systems [14].

4.5. Model of the "Onboard" System:

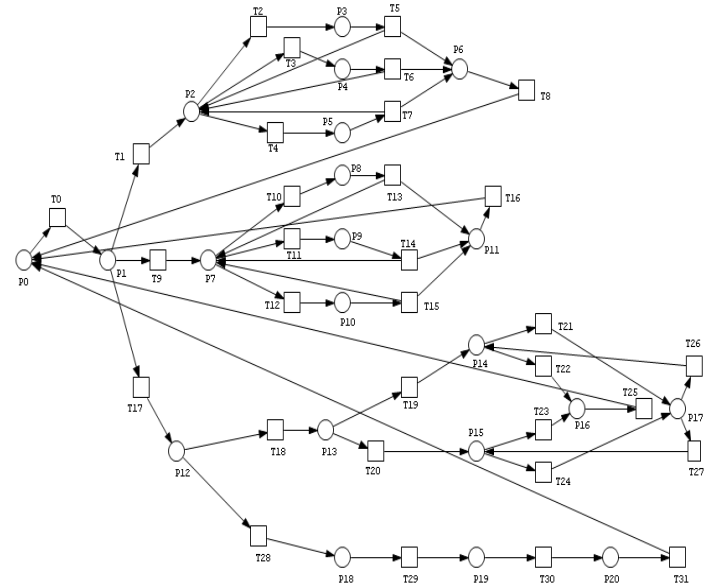


Figure.6Petri Net model of the "Onboard" system

The " Onboard" system is modelled by the graph of stochastic Petri Net represented in **Figure 6**.

Table 3.Meaning of places and transitions of the "Onboard" system

Place	Meaning	Transition	Meaning
P0	Waiting	T0	Start
P2, P7, P12	Calculation	T1	Normal Onboard
P3, P8	Receive	T2, T10	Signal from track. (f>=900)
P4, P9	Send	T3, T11	Signal from train. (f<900)
P5	Operation by Operator	T4	Operation. (operator=1)
P10	Operation by computer	T5, T13	End send to train
P14	No receive	T6, T14	End send to track
P15	No send	T7, T15	End operation
P16	Correct order	T8, T16, T31, T25	End
P17	No send. No receive	T9	Degraded onboard
P19	Error state	T12	Operation. (operator=0)
P20	Correct sate	T17	failed onboard
		T18	order of error of net
		T19, T24	error train 2 track
		T20, T21	error track 2 train
		T22, T27	repair receive-OB
		T23, T26	repair send-OB
		T28	error state of net
		T29	network failed=1
		T30	Repair net

The meaning of the various places and transitions of the "onboard" system is given in the **table 3**.

4.6. Model of the "Trackside" and "GSM-R" Systems:

We modelled the two systems "Trackside" and "GSM-R" by the same model which is represented in **figure 7**.

The meaning of the various places and transitions of the "Trackside" and "GSM-R" systems is given in the tables 4 and 5.

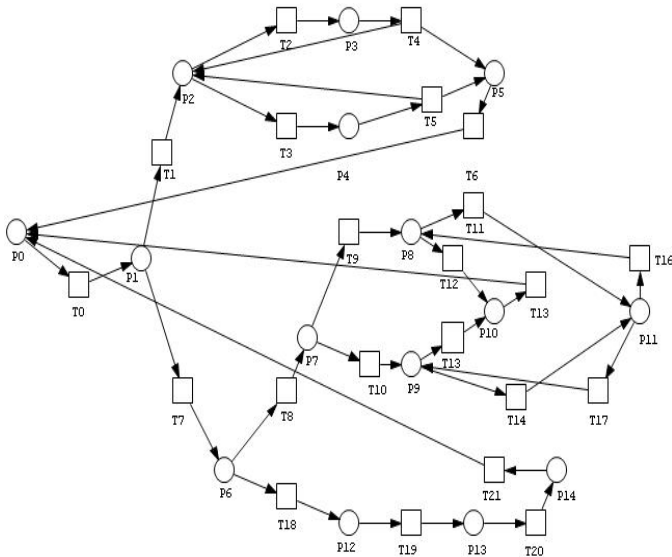


Figure.7 Model Petri Net of the "Trackside" and "GSM-R" systems

Table 4. Meaning of places and transitions of the "Trackside" system

Place	Meaning	Transition	Meaning
P0	Waiting	T0	Start
P1		T1	Normal trackside
P2,P6	Collection info calculation	T2	Signal from track. (f>=900)
P3	Send	T3	Signal from train. (f<900)
P4	Receive	T4	end send to train
P8	No receive	T5	end send to track
P9	No send	T6,T15,T21	End
P10	Correct order	T7	failed Trackside
P11	No send.No receive	T8	order of error of net
P13	Error state	T9, T14	error train 2 track
P14	Correct state	T12, T11	error track 2 train
		T12, T17	repair receive-TS
		T13, T16	repair send-TS
		T18	error state of net
		T19	network failed=1
		T20	Repair net

Table 5. Meaning of places and transitions of the "GSM-R" system

Place	Meaning	Transition	Meaning
P0	Waiting	T0	Start
P1		T1	Normal GSM-R
P2, p6	Collect message	T2	Signal from track. (f>=900)
P3	Send	T3	Signal from train. (f<900)
P4	Receive	T4	End send to train
P8	No train 2 track	T5	End send to track
P9	No track 2 train	T6,T15,T21	End
P10	Correct order	T7	Failed GSM-R
P11	No train 2 track. No track 2 train	T8	Order of error of net
P13	Error state	T9, T14	Error train 2 track
P14	Correct state	T10, T11	Error track 2 train
		T12, T17	Repair track 2 train
		T13, T16	Repair train 2 track
		T18	Error state of net
		T19	Network failed=1
		T20	Repair net

5. Simulation of the Petri Net Model: results and discussion

To evaluate the performances of the railway signalling system, we have to register the time which the components of the system spend in every State during the simulation. We take a step of simulation equal to $\Delta t=1h$ and we simulate the functioning of the system in the interval $[0, 100 h]$:

We take the following data for the events and the variables as well as their rates of transition or their probability [4]:

- Rate of transition (Operation, End Operation) = 0.95
 - Rate of transition (Signal From Track, End Send To Train, Signal From Train, End Send To Track) = 0.4
 - $P(f < 900) = P(f \geq 900) = 0.5$
 - Rate of transition (operator=0) = $\lambda_{op} \cdot \Delta t$, Where $\lambda_{op} = 8.514 \cdot 10^{-5} h^{-1}$
 - Rate of transition (network_failed=1) = $\lambda_n \cdot \Delta t$, Where $\lambda_n = 9.3885 \cdot 10^{-6} h^{-1}$
 - Rate of transition (Repair Net) = $\mu_r \cdot \Delta t$, Where $\mu_r = 0.6 h^{-1}$
 - Rate of transition (ErrorTrain2Track, Error Track2Train) = $\lambda_r \cdot \Delta t$, Where $\lambda_r = 0.0001 h^{-1}$
 - Rate of transition (Repair Receive_OB, Repair Send_OB, Repair Receive_TS, Repair Send_TS, RepairTrack2Train, RepairTrain2Track) = $\mu_r \cdot \Delta t$, OÙ $\mu_r = 0.6 h^{-1}$
- For the first type "Error State Of Net", we have:
- Rate of transition (Failure) = $\lambda_n \cdot \Delta t$, Where $\lambda_n = 9.3885 \cdot 10^{-6} h^{-1}$
 - Rate of transition (Repair) = $\mu_r \cdot \Delta t$, Where $\mu_r = 0.6 h^{-1}$
- For the second type "Order of Error of Net", we have:
- Rate of transition (Failure) = $\lambda_r \cdot \Delta t$, Where $\lambda_r = 0.0001 h^{-1}$
 - Rate of transition (Repair) = $\mu_r \cdot \Delta t$, Where $\mu_r = 0.6 h^{-1}$

The "onboard" system works in three modes:

- Normal mode: it represents places between P2 and P6, and occupies a total of 20185 marks, then an average of 4037 marks by place.
- Degraded mode: it represents places between P7 and P11, and occupies a total of 20403 marks, then an average of 4080.6 marks by place.
- Failure mode: it represents places between P12 and P20, and occupies a total of 7647 marks, then an average of 849.667 marks

by place.

If we translate the previous results in terms of availability in the time interval [0, 100h], we obtained:

$$A1 = (4037 + 4080.6) / (4037 + 4080.6 + 849.667) = 0,90524798.$$

The look of the curves of variation of the marks of the previous places for the three modes of the "onboard" system is represented in the **figure 8**.

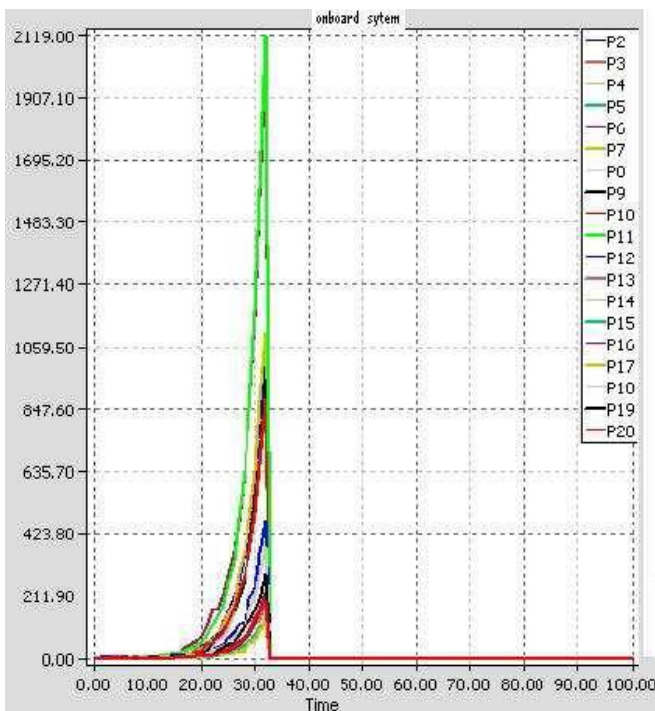


Figure.8 Variation of the marks of the places of the "onboard" system

For the "Trackside" system, it works in two modes:

- Normal mode: it represents places between P2 and P5, and occupies a total of 28099 marks, then an average of 7024 marks by place.

- Failure mode: it represents places between P6 and P14, and occupies a total of 2 marks, then an average of 0.22 marks by place.

If we translate the previous results in terms of availability in the time interval [0, 100h], we obtained:

$$A2 = (7024, 75) / (7024, 75 + 0, 22222222) = 0,99971537.$$

The look of the curves of variation of the marks of the previous places for the three modes of the "Trackside" system is represented in the **figure 9**

Similarly, the "GSM-R" system works in two modes:

- Normal mode: it represents places between P2 and P5, and occupies a total of 21800 marks, then an average of 5450 marks by place.

- Failure mode: it represents places between P6 and P14, and occupies a total of 4 marks, then an average of 0.44 marks by place.

If we translate the previous results in terms of availability in the time interval [0, 100h], we obtained:

$$A3 = (5450) / (5450 + 0, 44444444) = 0,99926659$$

The look of the curves of variation of the marks of the previous places for the three modes of the "GSM-R" system is represented in the **figure 10**.

So that all the system is available, the three systems have to be available, thus the availability of the railway signalling system is $A = A1 \cdot A2 \cdot A3 = 0,90432659$.

We proceed in the same way for the intervals of time [0, 1000 h]

and [0, 10000 h] and we find then successively:

$$A' = 0,91097923 * 0,99990678 * 0,99995634 = 0,91085454$$

$$A'' = 0,90291262 * 0,9999745 * 0,99993636 = 0,90283214$$

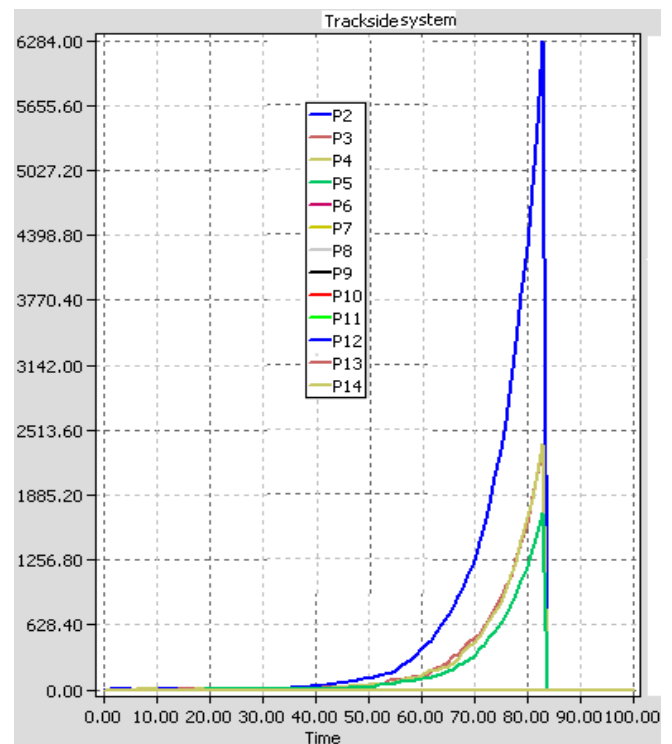


Figure.9 Variation of the marks of the places of the "Trackside" system

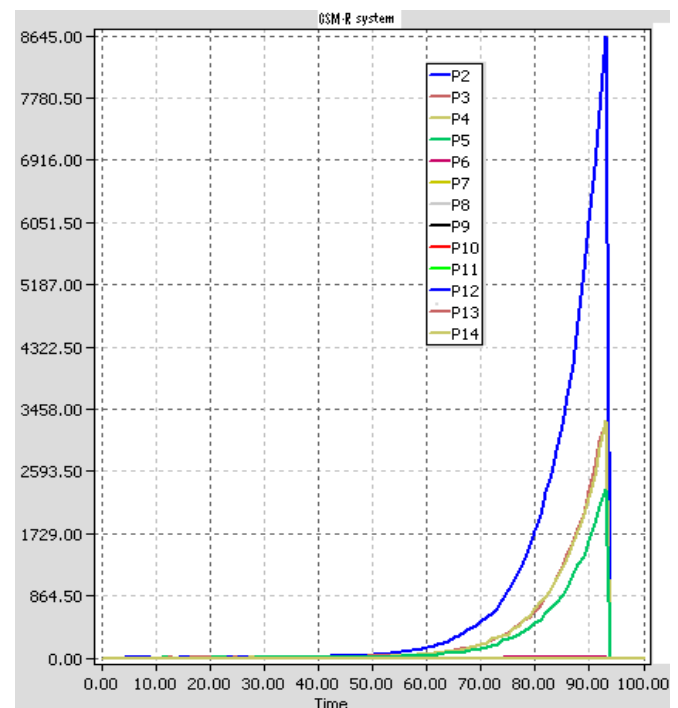


Figure.10 Variation of the marks of the places of the "GSM-R" system

6. Conclusion

In this article, the availability of the railway signalling system "ERTMS" was computed by computing the availability of the three system components based on the Stochastic Petri Nets, by taking into account the human factor and network failures using,

the United States data of accidents.

In our future works, we wish to enrich our model, by introducing the consideration of aleatory and epistemic uncertainties of reliability data using Moroccan accidents statistics, as well as the use of other methods like "Fault Tree Analysis", "Valuation Based Systems" and "Fuzzy Logic".

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