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Reliability Analysis on ATP System of CTCS-3 based on D-S Evidence Inference and Bayesian Network

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Abstract

Taking account of the influence of uncertainty, incomplete issues and common cause failure (CCF) to system reliability, a method for reliability analysis based on Dempster-Shafer (D-S) evidence inference and Bayesian network (BN) is proposed by using the advantage of uncertainty reasoning and figurative expression of BN. Firstly, the method to map fault tree into BN with epistemic uncertainty is presented, and the probability of top event (TE) is calculated by belief measure and plausibility measure of evidence. Moreover, by using BN, some useful information can be obtained, through which the weak parts of the system can be identified. The results demonstrate that the proposed method makes a more rational evaluation result, and it is quite valid to deal with uncertainty information in reliability analysis, which provide a reasonable guidance for system fault diagnosis and maintenance and improve the system reliability.

Keywords: *Reliability analysis; ATP system of CTCS-3; Bayesian network; Evidence inference; Common cause failure; Epistemic uncertainty*

1. Introduction

China train control system (CTCS-3) is a safety-critical system, which features complex structure, redundant configuration, where the phenomenon of common cause failure is prevalent. As a core equipment of CTCS-3, Automatic train protection (ATP) system plays an important role in ensuring the safety, reliability and efficient operation on high-speed railway [1,2]. Therefore, its reliability analysis possesses pretty important significance.

Fault Tree Analysis (FTA) and Markov model are very popular for the reliability modeling and assessment of large, safety-critical systems, which have been widely applied in railway signaling [3-6]. However, FTA method cannot deal with the failure correlation problems because of its localization in reliability analysis such as independence among components, and with the number of basic events and logic gates increase, the solution precision will be degraded [7]. Markov model can figure out the modeling of a system with failure dependency, however, it faces with the issue of state space explosion as the number of components in the system increases, the construction and solution of Markov model are tedious and prone [8]. Both of the two methods mentioned above, the probability of event is supposed as an accurate value. Actually, it is very difficult to obtain the exact numerical value because of lack of experimental data and failure data at the design stage, in addition, the failure rate is affected by the external environment factors. Thus, it will lead to epistemic uncertainty that will affect the reliability analysis of system [9]. Therefore, it is necessary to develop a new method to estimate the system reliability.

Bayesian network (BN) has very strong capability to handle a large scale system, common cause failure and represent the uncertainty of variables, which is widely used in reliability research to solve the uncertainty and incomplete issues effectively [10,11,12].

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Dempster-Shafer (D-S) evidence theory can reduce the dependence on the original information by quantifying uncertainty information [13,14].

In this paper, a method which is combined by the D-S evidence theory and Bayesian network for reliability assessment of ATP system is proposed, which can weaken the effect of imperfection of the original parameters or subjective parameters in the reliability evaluation. It is able not only to compute the system reliability indices but also to analyze easily the effects of a certain components on the system reliability to find the weak links of the system, which is helpful to enhance the system reliability. The tool of MSBNX simplifies the counting process efficiently.

2. Description of the ATP system

2.1. Structure and function of ATP system

ATP is the indispensable device of high speed train because it is in charge of controlling train movement against a permitted speed profile (braking or protection curve). In order to perform train protection, the ATP system must be equipped with the following devices: Vital Computer (VC), Train Interface Unit (TIU), Speed and Distance Unit (SDU), Track Circuit Information Receiver (TCR), Radio Transmission Module (RTU), Radio Station (RSS), GSM for Railway (GSM-R), Balise Transmission Module (BTM), BTM Antenna, Driver Machine Interface (DMI), Juridical Recorder Unit (JRU). The VC involves CTCS-3 control unit and CTCS-2 control unit, and the two units are set independently but running at the same time. The former takes charge of the core control function as CTCS-3 train control system works normally, and the latter takes charge of the control function of spare system (CTCS-2). Structure diagram of ATP system is given in Figure.1.

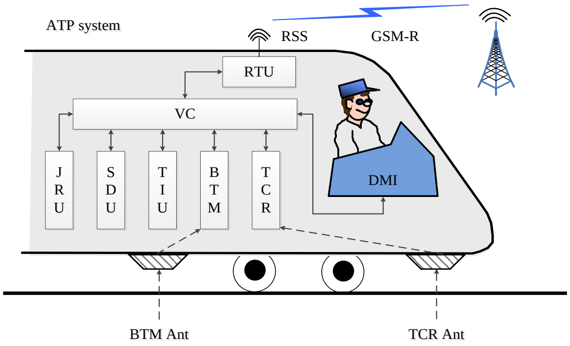


Figure 1. Structure Diagram of ATP System

2.2 Fault Tree Model of ATP System

FTA is a figure deductive method, which can realize the logical reasoning of failure event under certain conditions. This method is based on the identification of a particular undesired event to be analyzed, called Top Event (TE). FTA is carried out in two steps: qualitative and quantitative analysis. The first step in which the logical expression of the TE is derived in terms of the minimal cut sets, and the second step in which, on the basis of the probabilities assigned to the failure events of the basic components, the occurrence probability of the TE is calculated.

ATP system is a real-time and safety-critical computing system, so most of the key equipment are based on the well-known and highly adopted hot standby redundant architecture, such as VC, TIU, TCR, RTU, et al. From the perspective of system function, the main function of ATP is to realize the train operation against a permitted speed profile. Therefore, we can neglect the units that have no impacts on the main function when establishing the fault tree model of ATP. According to the steps of FTA, ATP failure is selected as the TE. The fault tree model for the ATP system is depicted in Figure 2. The logical expression of the TE as a function of the minimal cut sets is given by the following expression:

$$TE=B1B2+D8+D9+D10+D11 \tag{1}$$

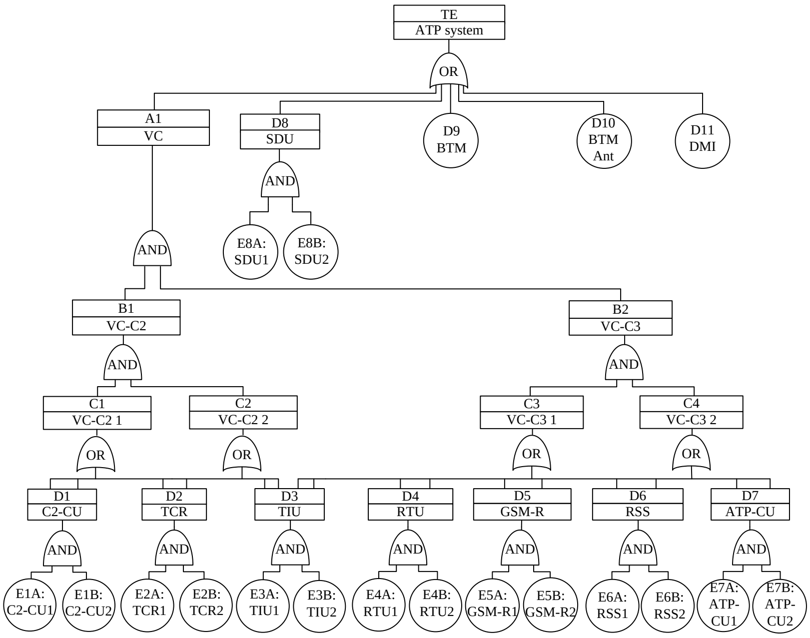


Figure 2. The Fault Tree Model for the ATP System

We will realistically assume that the ATP system is irreparable on-line. Moreover, it only features a failure mode related to availability, that is, at any time it can only assume two states: available and unavailable. Furthermore, we assume that the components of ATP obey the exponential distribution. The code, name and failure rate of the basic units in the fault tree of ATP are shown by Table 1, which come from the reference [15].

Table 1. Failure Rate of the Basic Units in ATP

Event number	Event code	Event name	Failure rate
1	E1	C2-CU	1.20×10^{-5}
2	E2	TCR	2.30×10^{-6}
3	E3	TIU	2.10×10^{-5}
4	E4	RTU	1.80×10^{-5}
5	E5	GSM-R	1.45×10^{-8}
6	E6	RSS	1.20×10^{-5}
7	E7	ATP-CU	1.49×10^{-5}
8	E8	SDU	2.50×10^{-9}
9	D9	BTM	2.00×10^{-6}

Continued from Table 1

10	D10	BTM Ant	7.00×10^{-8}
11	D11	DMI	5.00×10^{-6}

3. Theory of BN and Evidence inference

3.1. Bayesian Network

BN is a directed acyclic graph (DAG), which is based on the theory of probabilistic reasoning to express the relationship between random variables. Variables are also called nodes. A Bayesian network is made up of a DAG and a set of Conditional Probability Table (CPT) [16]. In the DAG, there are some nodes denoting random variables and directed arcs between pairs of nodes representing dependencies relationship between them. In the BN, there are three types of nodes: root node, sub-node and leaf node.

The basic inference task of BN is calculating the occurrence probability of TE. Suppose A_i (i=1,2,…,n) and B are random variables, and the probability of event B is not zero, that is $P(B)>0$. According to the Bayesian formula, $P(A_i \mid B)$ can be expressed as,

$$P(A_i \mid B)=\frac{P(A_i)P(B \mid A_i)}{\sum_{i=1}^{n} P(A_i)P(B \mid A_i)} \tag{2}$$

Where $P(A_i \mid B)$ is that the conditional probability of event A_i on condition that event B has happened. $P(A_i)$ is the prior probability, and $P(A_i \mid B)$ is the posteriori probability of A. Based on the total probability formula, $P(B)$ is defined as follows,

$$P(B)=\sum_{i=1}^{n} P(B \mid A_i)P(A_i) \tag{3}$$

The advantages of BN in analyzing problems lie in its bidirectional reasoning, it is very convenient to derive the TE occurrence probability from prior probability by forward reasoning and then analyze the reliability of system. The backward reasoning also makes it easy to realize the weak links of system and carry out fault diagnosis [17].

3.2. D-S Evidence Inference

The D-S evidence theory provides a description of both imprecision and uncertainty by the definition of two functions: plausibility (Pl) and belief (Bel). Let Θ be a space of hypotheses, and A is the set of the subsets of Θ. Mass function (m) is defined for the element A of 2^{Θ}, such that the value of 2^{Θ} belongs to the [0,1] and,

$$\begin{cases} m(\varnothing)=0 \\ \sum_{A\subseteq\Theta} m(A)=1 \end{cases} \tag{4}$$

Where m (A) is the basic probability assignment (BPA) of event A, and $\varnothing$ is the empty set.

The plausibility (Pl) and belief (Bel) functions, both derive from m, are defined from mass function, respectively,

$$\mathrm{Bel}(A)=\sum_{B\subseteq A} \mathrm{m}(B) \tag{5}$$

$$\mathrm{Pl}(A)=\sum_{B\cap A\neq\varnothing} \mathrm{m}(B) \tag{6}$$

These two functions, which have been sometimes referred to as belief and plausibility measurement, have the following properties,

$$\begin{cases} \mathrm{Bel}(A) \le \mathrm{Pl}(A) \\ \mathrm{Bel}(A) = 1 - \mathrm{Pl}(A) \end{cases} \tag{7}$$

From this formula, can we conclude that for the trusted measure of event A, $\mathrm{Pl}(A)$ is more optimistic than $\mathrm{Bel}(A)$, namely, $\mathrm{Bel}(A)$ is estimated to be more conservative than $\mathrm{Pl}(A)$. We denote $P(A)$ the true value of trusted measure of event A and,

$$\mathrm{Bel}(A) \le P(A) \le \mathrm{Pl}(A) \tag{8}$$

Thus it provides Bel (A) and Pl (A) which are the lower and upper probability of $P(A)$ respectively.

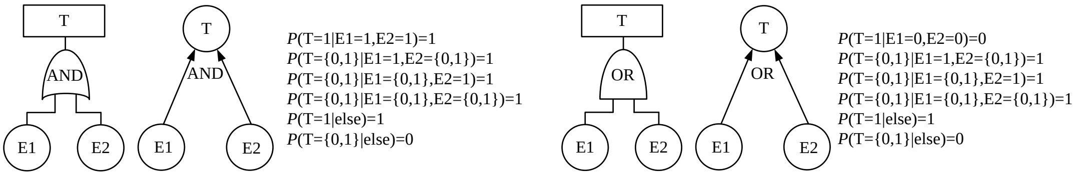
3.3. BN Expansion Based on Evidence Theory

3.3.1 BN Model with Epistemic Uncertainty:

For ease of description, we suppose that basic event E only features two states, and denote “1” and “0” the event happens and does not happen respectively. Then $\Theta = \{0,1\}$ and,

$$\begin{gathered} 2^{\Theta} = \{m(\mathrm{E} \ne \varnothing) = 0; m(\mathrm{E} = \{1\}); \\ m(\mathrm{E} = \{0\}); m(\mathrm{E} = \{0,1\})\} \end{gathered} \tag{9}$$

Where {0,1} is the uncertainty of event occur or not, which express epistemic uncertainty [18]. The expression of BN nodes of logical gates with epistemic uncertainty are shown in Figure 3.



(a) Mapping of logical AND gate (b) Mapping of logical OR gate

Figure 3. BN Model with Epistemic Uncertainty

3.3.2. Reliability Prediction:

It is very convenient to calculate the probability of TE through the forward reasoning of BN without counting the minimum cut sets, which can realize the reliability prediction. The probability of TE can be obtained according to the joint probability distribution.

$$P(\mathrm{TE} = 1) = \sum_{\mathrm{E1},\ldots,\mathrm{E}n} P(\mathrm{E1} = \mathrm{e1}, \ldots, \mathrm{E}n = \mathrm{e}n, \mathrm{T} = 1) \tag{10}$$

Where E1,E2,…,En are the root nodes in BN, TE is the leaf node. ei is the state of Ei and ei belongs to the [0,1].

The uncertainty will transfer from root node to the sub-node and leaf node through the BN when the root node with cognitive uncertainty [9]. Thus the probability of sub node M is not an accurate value but a numeral area, the lower and upper probability are obtained by Bel (M=1) and Pl (M=1), respectively. Probability model of sub-node in BN is shown in Figure 4.

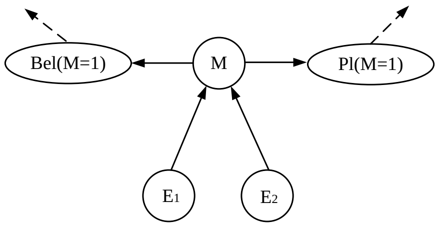


Figure 4. Probability Model of Sub-Node with Epistemic Uncertainty in BN

The state of M can be determined according to the conditional state diagram as shown in Figure 3. Base on the state of M, Bel (M=1) and Pl (M=1) can be achieved refer to Formula (5) and (6), as shown in Table 2. In the following, we can calculate the Bel (T=1) and Pl (T=1) by BN reasoning depend on Table 2, Figure 1 and Formula 10, thus P (T=1) belongs to [Bel (T=1),Pl (T=1)].

Table 2. Bel and Pl of Sub-Node

State of M	Bel (M=1)	Pl (M=1)
0	0	0
1	1	1
0_1	0	1

3.3.3. Importance Analysis:

Importance analysis is a significant component of quantitative analysis and an important concept in reliability engineering. We can identify the weak points of the system and prioritize the system design. It is very convenient to calculate the three types of basic event importance by using clique tree, variable elimination and bucket elimination [19]. The probability importance, structure importance and key importance can be obtained by,

$$I_i^{\mathrm{P}} = P\left(\mathrm{T}=1 \mid \mathrm{E}i=1\right) - P\left(\mathrm{T}=1 \mid \mathrm{E}i=0\right) \tag{11}$$

$$I_i^{\mathrm{S}} = P\left(\mathrm{T}=1 \mid \mathrm{E}i=1, P\left(\mathrm{E}j=1\right)=0.5\right) - P\left(\mathrm{T}=1 \mid \mathrm{E}i=0, P\left(\mathrm{E}j=1\right)=0.5\right) \tag{12}$$

Where, $1 \le j \ne i \le n$。

$$I_i^{\mathrm{C}} = \frac{P\left(\mathrm{E}i=1\right)}{P\left(\mathrm{T}=1\right)} \times \left[P\left(\mathrm{T}=1 \mid \mathrm{E}i=1\right) - P\left(\mathrm{T}=1 \mid \mathrm{E}i=0\right)\right] \tag{13}$$

Actually, the importance $P(\square)$ are interval number except the structure importance due to the epistemic uncertainty, we can set it as the average of $\mathrm{Bel}(\square)$ and $\mathrm{Pl}(\square)$, that is,

$$P(\square) = (\mathrm{Bel}(\square) + \mathrm{Pl}(\square))/2 \tag{14}$$

The above importance does not reflect the influence of uncertainty on reliability and for this epistemic importance is proposed in this paper. Epistemic importance is a kind of metric indicator of top event uncertainty which caused by the uncertainty of basic events [9]. It can be calculated by the following expression,

$$\begin{gathered} I_i^{\mathrm{E}} = \mathrm{Pl}(\mathrm{T}=1 \mid \mathrm{cond.}) - \mathrm{Bel}(\mathrm{T{=}1|cond.}) \\ \mathrm{cond.{:}m}(\mathrm{E}i{=}\{0,1\}) \ne 0, \mathrm{m}(\mathrm{E}j{=}\{0,1\}){=}0, i{=}1,2,\ldots,n,\ j=1,2,\ldots,n,\ j \ne i \end{gathered} \tag{15}$$

It is very convenient to obtain that which basic event uncertainty has a biggest influence on system reliability analysis, thus we can take some measures to reduce the uncertainty.

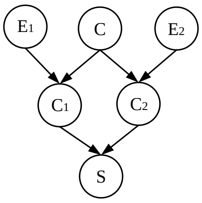
4. Common Cause Failure

Common cause failure (CCF) is a kind of failure caused by the same reason and lead to two or more devices invalid at the same time or within a very short time.

The key to construct a CCF model of system reliability by using BN is to divide the common cause component failure rate λ into an independent failure rate λ_I and CCF rate λ_C [20]. The BN of a parallel system with two components considering CCF is shown in Figure 5. Here, E_i (i=1,2) is the independent failure factor of C_i (i=1,2). C is the common cause failure factor of C_i (i=1,2). For systems with two states: "0" present the component is in normal and "1" means the component is failed, and the failure of the whole system is as follows,

$$\lambda = \lambda_{E_1}\lambda_{E_2} + \lambda_C \tag{16}$$

E1	C	$P(C_1=1 \mid E_1,C)$
0	0	0
0	1	1
1	0	1
1	1	1



C1	C2	$P(S=1 \mid C_1,C_2)$
0	0	0
0	1	0
1	0	0
1	1	1

Figure 5. The BN of Parallel System Considering CCF

We denote R_S and R_C the reliability of system regardless of and considering CCF, respectively. Since E1=E2, the expression of system reliability can be expressed as follows,

$$R_S = 2P(E_1=0) - P^2(E_1=0) \tag{17}$$

$$\begin{aligned} R_C &= P(S=0) = \sum_{E_1,C,E_2,C_1,C_2,S} P(E_1,C,E_2,C_1,C_2,S) \\ &= \sum_{C_1,C_2} \{P(S=0 \mid C_1,C_2) \times \sum_{E_1,C} [P(C_1=0 \mid E_1,C)P(E_1)P(C)] \\ &\times \sum_{E_2,C} [P(C_2=0 \mid E_2,C)P(E_2)P(C)] \\ &= 2R_1R_{C^*} - R_1{}^2R_{C^*} \end{aligned} \tag{18}$$

Here, $R_1 = P(E_1=0)$, $R_{C^*} = P(C=0)$.

Now let $\lambda_1 = \lambda_2 = 0.005$, $\beta = 10\%$, with this information the reliability curves of parallel system are shown in Figure 6. It can be seen that $R_S(t)$ is greater than $R_C(t)$ at the same time in parallel system, and the common cause failure will greatly affects system reliability. So the CCF should not be ignored in the reliability analysis.

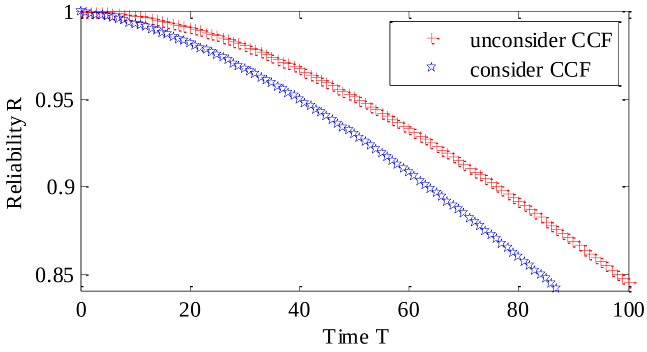


Figure 6. Contrast Curves of Parallel System Reliability

5. Reliability Analysis of ATP

In accordance with the approach for mapping FT into BN, the BN model ATP is established by MSBNX as shown in Figure 7.

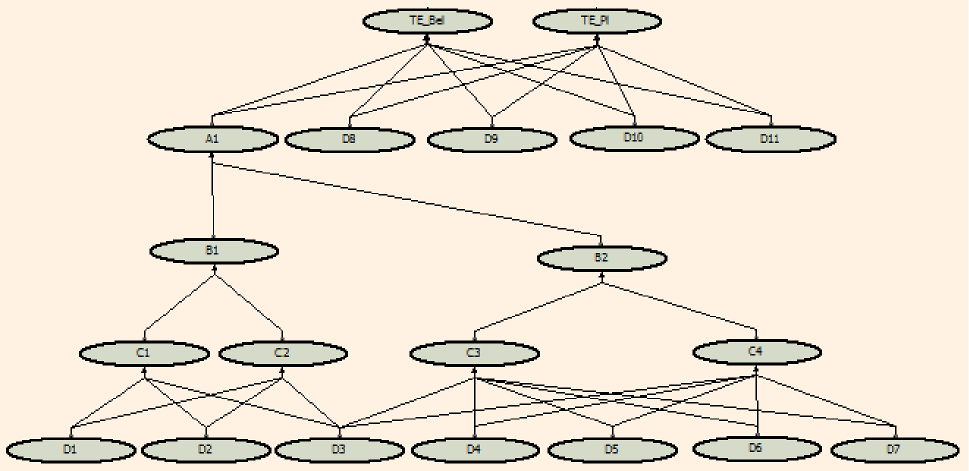


Figure 7. BN Model of ATP System

As ATP system is a safety-critical system and the majority of equipment in it are redundant configuration. Therefore, we must consider CCF in the reliability analysis of ATP system. Table 3 shows the failure of basic units, where λ_I and λ_C represent the independent failure rate and common cause failure rate, respectively. According to the formula (16), it is easy to obtain the failure of basic units (λ_U). The failure of basic unit is presented by interval number in consideration of the uncertainty involved in reliability analysis, and we marked it with λ_{UF} . Taking differ with 15% of λ_U as the upper and lower boundary of λ_{UF} by reference to the principle of determining fuzzy number that is presented by Dubois and Prade.

Table 3. Reliability Parameters of Basic Units

Node	Name	λ_I /h-1	λ_C /h^{-1}	λ_U /h^{-1}	λ_{UF} /h^{-1}
D1	C2-CU	1.20×10^{-5}	1.20×10^{-6}	1.20×10^{-6}	$[1.02\times10^{-6},1.41\times10^{-6}]$
D2	TCR	2.30×10^{-6}	2.50×10^{-7}	2.50×10^{-7}	$[2.13\times10^{-7},2.94\times10^{-7}]$
D3	TIU	2.10×10^{-5}	1.94×10^{-6}	1.94×10^{-6}	$[1.65\times10^{-6},2.28\times10^{-6}]$
D4	RTU	1.80×10^{-5}	1.71×10^{-6}	1.71×10^{-6}	$[1.45\times10^{-6},2.01\times10^{-6}]$
D5	GSM-R	1.45×10^{-8}	1.61×10^{-9}	1.61×10^{-9}	$[1.37\times10^{-9},1.89\times10^{-9}]$
D6	RSS	1.20×10^{-5}	1.20×10^{-6}	1.20×10^{-6}	$[1.02\times10^{-6},1.41\times10^{-6}]$
D7	ATP-CU	1.49×10^{-5}	1.45×10^{-6}	1.45×10^{-6}	$[1.23\times10^{-6},1.71\times10^{-6}]$
D8	SDU	2.50×10^{-9}	2.78×10^{-10}	2.78×10^{-10}	$[2.36\times10^{-10},3.27\times10^{-10}]$
D9	BTM	2.00×10^{-6}	—	2.00×10^{-6}	$[1.70\times10^{-6},2.35\times10^{-6}]$
D10	BTM Ant	7.00×10^{-8}	—	7.00×10^{-8}	$[5.95\times10^{-8},8.24\times10^{-8}]$
D11	DMI	5.00×10^{-6}	—	5.00×10^{-6}	$[4.25\times10^{-6},5.88\times10^{-6}]$

Combining BN with D-S evidence theory, the belief probability and plausibility probability of ATP system failure are calculated according to forward reasoning, as shown in Table 4. The failure of ATP system belongs to [0.000766%,0.001059%], thus the availability range from 99.9989% to 99.9992% which satisfy the requirements of CTCS requirements specification. Setting time as 2×10^4h, then the reliability is presented in Figure 8.

Table 4. Bel and Pl of ATP System

node	Bel(TE=1)/%	Pl(TE=1)/%
T	0.000766	0.001059

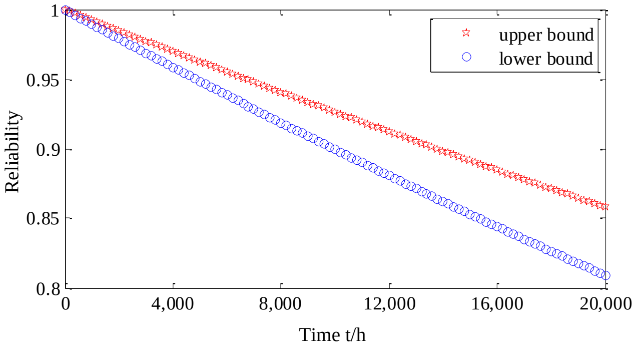


Figure 8. The Reliability Curves of ATP System

Based on the analysis in section 3.3.3, it is convenient to calculate the three types of common importance and epistemic importance of basic unit, the results are shown in Table 5. It is shown that the uncertainty and epistemic importance of basic event have not the same sequence, which means that the uncertainty does not reveal the impact on the system reliability of the TE. In addition, we also obtain the uncertainty of DMI, BTM and TIU has a crucial influence on ATP system reliability from the epistemic importance.

Table 5. Importance of ATP System

Node	uncertainty	I_i^{P}	I_i^{C}	I_i^{S}	I_i^{E}
D1	0.39×10^{-6}	4.36×10^{-6}	5.81×10^{-7}	0.014649	0
D2	0.81×10^{-7}	4.36×10^{-6}	1.21×10^{-7}	0.014649	0
D3	0.63×10^{-6}	0.999993	0.215309	0.018555	0.63×10^{-6}
D4	0.56×10^{-6}	1.45×10^{-6}	2.75×10^{-7}	0.002930	0
D5	0.52×10^{-9}	1.45×10^{-6}	2.59×10^{-10}	0.002930	0
D6	0.39×10^{-6}	1.45×10^{-6}	1.93×10^{-7}	0.002930	0
D7	0.48×10^{-6}	1.45×10^{-6}	2.33×10^{-7}	0.002930	0
D8	0.91×10^{-10}	0.999991	3.09×10^{-5}	0.018555	9.00×10^{-11}
D9	0.65×10^{-6}	0.999993	0.221968	0.018555	0.65×10^{-6}
D10	2.29×10^{-8}	0.999991	0.007769	0.018555	2.29×10^{-8}
D11	1.63×10^{-6}	0.999996	0.554921	0.018555	1.63×10^{-6}

Applying backward reasoning to ATP system, it is supposed that the TE happens (assuming TE=1), the conditional probability of basic event failure is shown in Table 6.

Table 6. Diagnosis Reasoning of ATP System

Node	$P(\mathrm{D}i=1\|\mathrm{TE}=1)$	Event code	$P(\mathrm{D}i=1\|\mathrm{TE}=1)$
D1	1.78×10^{-6}	D7	1.68×10^{-6}
D2	3.71×10^{-7}	D8	3.09×10^{-5}
D3	0.21531	D9	0.22197
D4	1.99×10^{-6}	D10	0.00777
D5	1.87×10^{-9}	D11	0.55492
D6	1.39×10^{-6}		

According to Table 6, it is obvious that when the ATP system is failed, TIU is the most vulnerable link of ATP system except the double cold standby unit. Therefore, the weak links of ATP system are DMI, BTM, BTM Ant and TIU. From analysis above, to increase the reliability of ATP system, we should pay attention to maintenance of the aforementioned four units.

6. Conclusion

In this paper, we have used D-S evidence inference and BN for reliability analysis of ATP system with uncertainty and common cause failure. The results show that CCF has a greatly effect on reliability analysis, and the analysis result will introduce serious error under the hypothesis of independent failure. BN is very suitable to recognize the vulnerable positions of system, and TIU is the weak part of ATP system except the double cold standby unit, we should pay more attention to maintenance them in order to enhance the reliability. Demonstrated by an example, combined evidence inference with BN can resolve the influence of CCF and uncertainty, and improves the ability of BN to deal with the uncertainty in reliability analysis, which makes the analysis results more reasonable.

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