DOI 10.20544/HORIZONS.B.05.1.18.P05
UDC 656.216.2:656.259]:519.873(497.11)

APPLICATION OF FUZZY FAULT TREE ANALYSIS FOR DETERMINATION OF RAILWAY CROSSING RELIABILITY

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Abstract

Fault tree analysis (FTA) is one of the basic and most used methods for safety and reliability analysis of technical systems. This method is especially suitable for analysis system, which failures can cause serious consequences that affect on human lives and environment.

Railway crossings, as places of crossroads of road and rail traffic, constitute one of the most important sources of potential conflicts and accidents in the railroad domain. The probability of occurrence of an unwanted event is increased if the participants in the traffic do not respect the rules or if a malfunction has occurred on the technical device of the railway crossing. In this paper FTA model was created in combination with fuzzy logic. Fuzzy logic in this model is used to represent imprecisely probabilities of failure of the system.

By using the technique we proposed herein, values are transformed into the fuzzy numbers to give a realistic estimate of failure possibility of a basic event in FTA. The aim of this paper was to form a model which can identify scenarios and events that have the most affect on unwanted top event. This can lead to reduce number of accidents on railway crossing.Model was tested for one railway crossing in Pirot for basic top event "Passing the train by the unsecured railway crossing". Final ranking on events by their impact on failure of system was done through fuzzy importance index.

Key words: FTA, fuzzy, FII, railway crossing, failure

INTRODUCTION

One of the biggest transport and traffic problem is their safety. In recent years, some railway accidents have happened and caused a lot of injuries, fatalities, traffic interruption and costs. Big part in railway accidents are accidents on railway crossings. Therefore, special attention must be paid on railway crossing safety and reliability.

Fault tree analysis is proved to be a very effective tool to predict probability of hazard caused by a human mistake or technical failure of the system, which can be happened on railway crossing. In conventional FTA the basic events are represented by the probabilities (crisp numbers). However, for many systems available data are insufficient for statistical inference and it is very difficult to estimate failure possibilities of basic and undeveloped events. This was reason to combine conventional FTA with new approaches like fuzzy logic. There is many papers that implementing fuzzy logic in FTA [1,2,3,4, and 5,6].

FAULT TREE ANALYSIS

Fault tree analysis was developed in 1961 at Bell Telephone Laboratories. This technique provides graphical approach to the identification of high-risk areas. Method consists of direct computation from the probabilities of the primary events. Construction of a fault tree begins with the definition of the top undesired event. The formation of fault tree is done using symbols for different types of events: "circle" for primary events, "rectangle" for intermediate events or "rhombus" for undeveloped events. Logical symbols in the fault tree indicate the mutual conditionality and connection of the events of the lower and higher levels. For that purpose, we use "OR" logical gate if the occurrence of either input event causes the output event to occur. On the other hand, if both input events must occur in order the output event to occur, then they are connected using "AND" gate.

Minimal cut set is combination of components or events whose simultaneous failures lead to undesirabletop event. In order to determine the minimal cut set of the fault tree analysis, it is necessary to transform the tree into corresponding Boolean equations [7].

FUZZY NUMBERS AND OPERATIONS

Fuzzy set theory is a suitable mathematical tool for modeling different processes dominated by uncertainty, versatility, uncertainty and so on [8]. In a universe of discourse X, a fuzzy subset A of X is characterized by a membership function $f_A(x)$ which associates with each element x in X a real number in interval [0,1] [9].

Membership function triangular fuzzy number A can be described as [8]:

$$\mu_A(x)\begin{cases} 0, x \le a_1 \\ \left(\dfrac{x-a_1}{a_2-a_1}\right), a_1 \le x \le a_2 \\ \left(\dfrac{a_3-x}{a_3-a_2}\right), a_2 \le x \le a_3 \\ 0, x \ge a_3 \end{cases} \tag{1}$$

Operations on triangular and trapezoidal fuzzy numbers are as following [7].The addition of two fuzzy number A and B is defined as [8]:

$$A(+)B = (a_1, a_2, a_3) + (b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \tag{2}$$

Similarly subtraction of two triangular fuzzy numbers is also a triangular fuzzy number and it can be given by the following expression [8]:

$$A(-)B = (a_1, a_2, a_3) - (b_1, b_2, b_3) = (a_1 - b_3, a_2 - b_2, a_3 - b_1) \tag{3}$$

Using algebraic operations on fuzzy numbers now we can obtain fuzzy operators corresponding to Boolean operators "AND" and "OR".

If p_1, p_2, p_n are the possibility of the basic event *i (i= 1, 2,.... n)* than operator "AND" can be defined as [10]:

$$p_{AND} = AND(p_1, p_2, ..., p_n) = \prod_{i=1}^{n} p_i \tag{4}$$

Where $\prod$ denotes the fuzzy multiplication and p_{AND} be the possibility if resulting event. If p_i represent triangular fuzzy number (a_1, a_2, a_3), then [10]:

$$p_{AND} = AND(p_1, p_2, ..., p_n) = \prod_{i=1}^{n} (a_1, a_2, a_3) = \left(\prod_{i=1}^{n} a_{i1}, \prod_{i=1}^{n} a_{i2}, \prod_{i=1}^{n} a_{i3}\right) \tag{5}$$

Similarly, operator "OR" can be defined as [10]:

$$p_{OR} = OR(p_1, p_2, ..., p_n) = 1 - \prod_{i=1}^{n} (1 - (a_1, a_2, a_3)) = \left(1 - \prod_{i=1}^{n} (1 - a_{i1}), 1 - \prod_{i=1}^{n} (1 - a_{i2}), 1 - \prod_{i=1}^{n} (1 - a_{i3})\right) \tag{6}$$

FUZZY IMPORTANCE INDEX (FII)

Ranking of basic events by their importance and impact on top event play a vital role in fault tree analysis. On improving the reliability of the event having greater importance, one can improve the reliability of the system. The fuzzy importance of any event is always calculated in the form of fuzzy importance index (FII).Let $p_t$be the failure possibility of the top event and p_{ti}be the possibility of occurrence of top event if the basic event *Ei* does not happen. The distance of $p_t$fromp_{ti} will determine the importance of a basic event *Ei*.

If the basic events are triangular fuzzy numbers, than we denote $p_t$andp_{ti} by the triplets (a_1, a_2, a_3) and (a_1^i, a_2^i, a_3^i) respectively. It concludes that fuzzy importance index (FII) may be defined as follows [2]:

$$FII(E_i) = \sqrt{(a_1 - a_1^i)^2 + (a_2 - a_2^i)^2 + (a_3 - a_3^i)^2} \qquad (7)$$

If basic event *Ei*has a greater importance than the other basic event *Ej* than distance between $p_t$andp_{ti} is greater than distance between $p_t$andp_{tj}.

Using this method all basic and undeveloped events can be ranked by their importance index.

FUZZY FAULT TREE OF RAILWAY CROSSING RELIABILITY

In this paper, fuzzy numbers are used to represent failure possibility of each basic event in fault tree analysis. For that purpose, triangular fuzzy numbers are used.

At the beginning, we must define undesirable „top event“. For this model, that event is „*Passing the train by the unsecured railway crossing*“. This event can be caused by human mistake or some technical failure of the system and elements of the system.

Failure probabilities for all basic and undeveloped events are represented by fuzzy numbers collected from experts from the field and real state from the field in recent years [11]. Based on this data, a model is created and it is presented on figure 1. Model is divided into two basic categories, branch B_1 refers to train passing the railway crossing with permission, and branch B_2 refers to train passing the railwaycrossing without permission. It can be seen there are a total of 40 events, of which 17 of them belong to basic events and 6 events are undeveloped events.

Using Boolean equations failure probability of top event was calculated. System failure probability was determined by quality analysis.Final step represent calculation of fuzzy importance index and ranking of basic and undeveloped events.

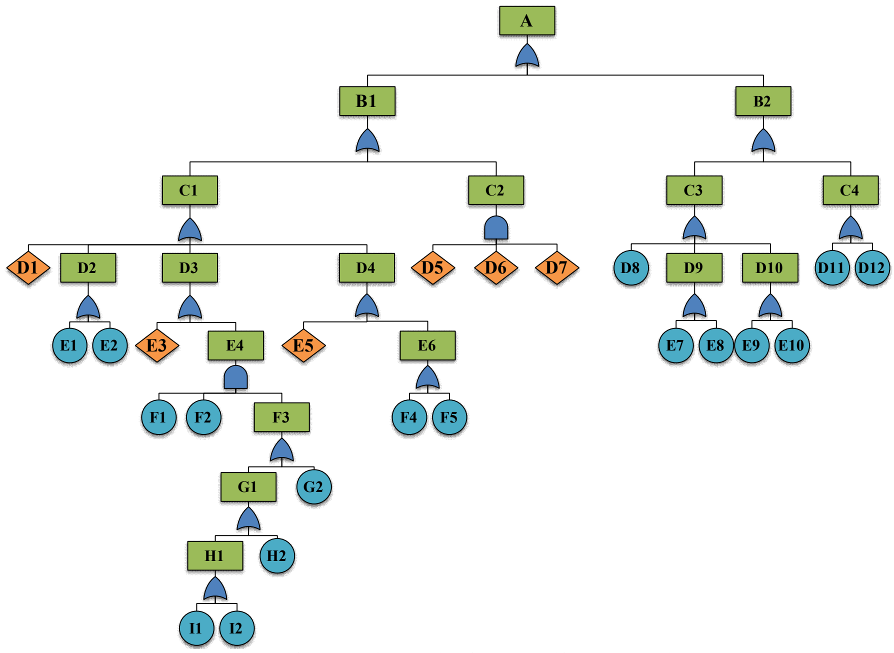

Figure 1. Fault tree of Westinghouse railway crossing

In the fault tree analysis, the following intermediate events appear:

- A - Passing the train by the unsecured railway crossing,
- B_1 - Train has permission for passing the railway crossing,
- B_2 - Train has not permission for passing the railway crossing,
- C_1 - Failure the device on railway crossing,
- C_2 - The device onrailway crossing correct, auxiliary fiber burned,
- C_3 - The train didn't stop in front of railway crossing ,
- C_4 - The train stopped in front of railway crossing,
- D_2 - The device is not activated after use of the crank,
- D_3 - Hitch on railway crossing device,
- D_4 - The device on railway crossing secured, barriers doesn't put down,
- D_9 - Poor assessment of train braking distance,
- D_{10} - Locomotive driver doesn't stop the train,
- E_4 - Main fiber burned,
- E_6 - Pointsman doesn't put down barriers at the railway crossing,
- F_3 - Contacts of the road signal control light bulb relay released,
- G_1 - Contacts for main fiber control relay released,
- H_1 - Signaling system mechanic changing the light bulb.

Owing to the complexity of decision environments or lack of sufficient data, each basic event of a fault tree is endowed with uncertain characteristic. Based on this, the failure possibilities of basic events are represented as fuzzy numbers shown in table 1.

Table 1. Basic events and their probabilities

Label	Basic event	a_1	a_2	a_3
D_8	Failure of braking system	0,008	0,012	0,014
D_{11}	Locomotive driver doesn't have order for passing the railway crossing	0,007	0,014	0,024
D_{12}	Locomotive driver stopped train in front of the railway crossing because of the failure of the signal	0,0033	0,0088	0,015
E_1	Relay failure	0,015	0,022	0,05
E_2	Control relay for closing half-barrier contacts closed	0,01	0,017	0,025
E_7	Locomotive driver fell asleep	0,004	0,011	0,023
E_8	Locomotive driver can't see the signal due to bad weather conditions	0,006	0,025	0,039
E_9	Irresponsible behavior of the locomotive driver	0,004	0,0055	0,0079
E_{10}	Locomotive driver can't stop the train because of health reasons	0,009	0,022	0,037
F_1	Contacts of the switching road signal relay released	0,004	0,007	0,1
F_2	Contacts of the flasher relay closed	0,001	0,025	0,04
F_4	Pointsman forgot to put down the barriers	0,002	0,008	0,014
F_5	Failure on push-button for put down the barriers	0,007	0,014	0,024
G_2	Invalid contact	0,03	0,075	0,099
H_2	Contacts of relay for hitch device on railway crossing released	0,06	0,088	0,099
I_1	Failure push-button „YES“ for returning relay in basic position	0,013	0,026	0,035
I_2	Relay main fiber failure	0,002	0,019	0,074

The corresponding assessment values for undeveloped events,denoted by triangular fuzzy numbers, are listed in table 2.

Table 2. Undeveloped events and their probabilities

Label	Undeveloped event	a_1	a_2	a_3
D_1	Broken pole half-barrier	0,01	0,023	0,034
D_5	Contacts of the relay for automatic or manual switch-on railway crossing device released	0,012	0,016	0,019
D_6	Contacts of the road signal switching relay released	0,009	0,015	0,035
D_7	Contacts of the one road signal light control relay released	0,04	0,081	0,1
E_3	Pole half-barrier aren't in regular position	0,04	0,06	0,08
E_5	Pointsman put down barrier on railway crossing	0,004	0,025	0,066

RESULTS

A top event can be expressed based on the basic and undeveloped events according to the fault tree diagram. Then, by utilizing the obtained failure possibilities of all basic and undevelopd events, the failure possibility of the top event can be calculated using Boolean equations, combined fuzzy logic with the arithmetic operations of triangular fuzzy numbers. The failure possibility of the top event can be represented as follow [12]:

$$\begin{aligned} A = &\left(\left(D_1 \cup \left(E_1 \cup E_2\right) \cup \left(E_3 \cup \left(F_1 \cap F_2 \cap \left(\left(\left(I_1 \cup I_2\right) \cup H_2\right) \cup G_2\right)\right)\right)\right.\right. \\ &\left.\cup \left(E_5 \cup \left(F_4 \cup F_5\right)\right)\right) \cup \left(D_5 \cap D_6 \cap D_7\right)\Big) \\ &\cup \left(\left(D_8 \cup \left(E_7 \cup E_8\right) \cup \left(E_9 \cup E_{10}\right)\right) \cup \left(D_{11} \cup D_{12}\right)\right) \end{aligned} \quad (8)$$

In the formulated fault tree of the Passing the train by the unsecured railway crossing, the membership function of the top event is expressed as [8]:

$$\mu_A(x) \begin{cases} 0, x \leq 0,12930474 \\ \left(\dfrac{x - 0,12930474}{0,1380511}\right), 0,12930474 \leq x \leq 0,26735584 \\ \left(\dfrac{0,4541945 - x}{0,1868386}\right), 0,26735584 \leq x \leq 0,4541945 \\ 0, x \geq 0,4541945 \end{cases} \quad (9)$$

To obtain the sequence for all basic and undeveloped events, first we calculate the failure possibility of top event if some event doesn't happen. The failure probability of top event for each basic and undeveloped event is listed in table 3.

Table 3. Probability of top event when basic (undeveloped) event doesn't happen

Basic events	D_8	0,12130474	0,255356	0,440195
	D_{11}	0,12230474	0,253356	0,430195
	D_{12}	0,12600474	0,258556	0,439195
	E_1	0,11430474	0,245356	0,404195
	E_2	0,11930474	0,250356	0,429195
	E_7	0,12530474	0,256356	0,431195
	E_8	0,12330474	0,242356	0,415195
	E_9	0,12530474	0,261856	0,446295
	E_{10}	0,12030474	0,245356	0,417195
	F_1	0,12930432	0,267319	0,452967
	F_2	0,12930432	0,267319	0,452967
	F_4	0,12730474	0,259356	0,440195
	F_5	0,12230474	0,253356	0,430195
	G_2	0,12930462	0,267343	0,453799
	H_2	0,1293045	0,26734	0,453799
	I_1	0,12930469	0,267351	0,454055
	I_2	0,12930473	0,267353	0,453899
Undeveloped events	D_1	0,11930474	0,244356	0,420195
	D_5	0,12930042	0,267336	0,454128
	D_6	0,12930042	0,267336	0,454128
	D_7	0,12930042	0,267336	0,454128
	E_3	0,08930474	0,207356	0,374195
	E_5	0,12530474	0,242356	0,388195

Focusing on studying which one is the most significant and influential basic or undeveloped event of a fault tree, a fuzzy importance index is used for ranking the events. Through comparing the outcomes, a sequence of importance index for all basic events can be obtained. Rank of fuzzy importance index of all basic and undeveloped events $E_i$are shown in table 4 (shaded events are undeveloped events).

Table 4. Ranking of basic and undeveloped events using fuzzy importance index

Event	Fuzzy importance index	Event	Fuzzy importance index
E_3	0,1077	F_4	0,0162
E_5	0,0707	E_9	0,0104
E_1	0,0566	F_1	0,0012
E_8	0,0467	F_2	0,0012
E_{10}	0,0440	H_2	0,0004
D_1	0,0422	G_2	0,0004
E_2	0,0318	I_2	0,0003
D_{11}	0,0287	I_1	0,0001
F_5	0,0287	D_5	0,0001
E_7	0,0258	D_6	0,0001
D_8	0,0201	D_7	0,0001
D_{12}	0,0177		

According to the table 4 and figure 2, it can be seen that largest FII and influence on top event "Passing the train by the unsecured railway crossing", has basic event E_3. The greatest impact on system failurehave events from branch B_1, which mostly represent technical part of fault tree. Also big influence have two basic events from branch B_2, $E_8$and E_{10} which represent how locomotive driver can affect on unwanted top event.

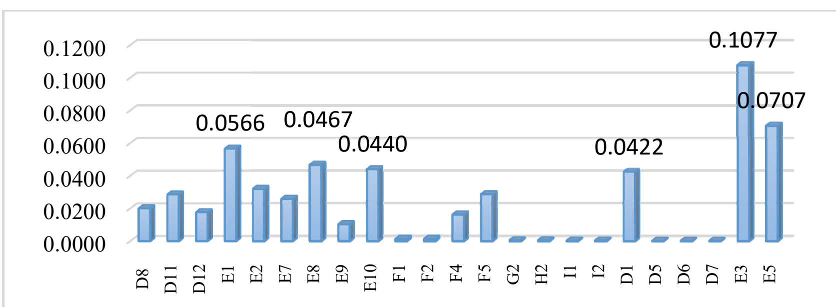

Figure 2. Fuzzy importance index of basic events

Figure 2 represent which basic and undeveloped events have a biggest impact on unwanted top event. There is a group of events with very high impact, about six events (data values shown on figure). Other events have less impact, and nine of them have very low impact on top event and they rarely can cause that train pass by unsecured railway crossing.

Data collected from the field shown that there is a connection between model results and real state. Main problems on this railway crossing in recent two years were defective left or right pole insert, and failure of fuse for right pole, in eight of ten cases. This accidents can be part of undeveloped event E_3 "Pole half-barrier aren't in regular position" which has largest influence on top event.

CONCLUSION

This paper focused on identification scenarios and events that can cause accidents on railway crossing like passing the train by the unsecured railway crossing. For that purpose, fuzzy FTA was used. Probabilities of basic and undeveloped events are defined on expert knowledge and situation on the field.

According to the Boolean algebra we calculate minimal cut set, and recalculate the failure possibilities of the top event in condition that one specific basic or undeveloped event did not occur. Main conclusions are drawn:

- most common causes of accidents on railway crossing from this paper are technical, so it is necessary to improve maintenance of railway crossing device and railway staffs responsibility in their usage and service;
- also, in the future, a change in the way of insurance can be considered, through the installing new modern devices on railway crossing;
- fuzzy numbers used herein, to represent failure possibility of basic or undeveloped events can be replaced with intutionistic fuzzy numbers to give more general results in fault tree analysis;
- model can be extended, some basic and undeveloped events can be even more branched, and more experts can be involved in defining the probability of this events and their influence on top event.

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