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ANALYSIS OF THE TRAIN DERAILMENT CAUSES USING FAULT TREE ANALYSIS[1]

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Abstract

The focus of this paper is put on the accidents consist of train derailments and scenarios that lead to them. It is carried out the qualitative analysis of scenarios that lead to accidents by applying the fault tree analysis (FTA). In the next phase, the quantification of the fault tree is applied. Considering quantified scenarios leads to the chain of events that has the highest probability of realization and which provides insight into the elements of procedure that is in such a chain the weakest link. As a result, there is a possibility of preventive react and to reduce the number of accidents as well as reduce severity of accidents can be realized as the consequences of such events. Research has been conducted on the basis of accidents that occurred on the Serbian railway network, in three-year period, 2012 - 2014. The total number of processed accidents is 1474, of which there were 312 derailments.

Key words - Risk Analysis; Security of Railway; Train Derailments; Accidents; Fault Tree Analysis

INTRODUCTION

The most common accidents on Serbian railways, are accidents occurring at level crossings, or derailments if shunting is being considered. In 2012, there were a total of 20 train derailments on Serbian Railways, which is about 4% of all railway accidents in Serbia ([1], [2]), and 81 derailments more occurred during shunting process. These data correspond to the data of EU [3], where in 2012 there were a total of 2294 railway accidents, of which 97 belong to the derailments (excluding derailments occurred during shunting process).

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[1] Original scientific paper

A derailment takes place when a railway vehicle (wagon, groups of wagons or train) runs off its rails. But it is not always understood that train completely fell out of track. Sometimes derailments are minor and imply just one bogy axle out of rail, without severe consequences. Although most of derailments are minor resulting in disruption of proper railway operation, they always present potentially seriously hazardous to human health and safety. Derailments may be caused by many causes as a collision with another train (or wagon), collision with an object, the mechanical failure of tracks (broken rails, tiles or sleepers), mechanical failure of the wheels, etc. Most common cause of derailment is broken rails or welds with over 15% of all derailments, and then track geometry with about 7% [4].

Derailment accident severity is often expressed by number of derailed wagons. The severity of derailment as accident is affected by numerous factors as train length [5], train speed (or speed of wagon or group of wagons) before derailment ([7], [8]) and the position of derailed wagon in train ([6], [8]).

The aim of the paper is to identify all the factors (scenarios) that could lead to derailment of the train or any of its part (shunting wagons). For this purpose, we used the methodology of fault tree analysis (FTA) that gives good results in such problems. The fault tree is a qualitative method (that can be quantified), which makes the possible to clearly determine the relationship between the events that lead to the realization of the top event (derailment of the train or shunting wagon), but also to determine the minimal cut sets of the tree [9]. Minimal cut sets of the fault tree are the minimum set of events whose realizations inevitably lead to the realization of the top event.

In the second phase, FTA allows the quantification of fault tree to be carried out and determination the probability of scenarios, i.e. events whose realization inevitably leads to the top event.

The advantage of this method it provides a clear insight into the existing connections between the events within the considered system and identification the weak points of it. The qualitative analysis yields of what elements of the system, in terms of safety, could be improved, increasing the safety in railway transport.

FAULT TREE ANALYSIS METHODOLOGY

To prepare the models, the first step imply collection of information about accidents, supported by an accident analysis. This step enables development of the model structure and providing information of probability of causes and impacts. Standard fault trees do not show neither specific safety measures nor functions.

This method consists of direct computation from the probabilities of the primary events. The method is based on the logically reduced tree, but the precision of the result is not lost. The procedure relies on the number of terms calculated using set theory, Boolean algebra and probability theory. The Calculation is computed by the expression for the top level probability. The complexity of this kind of calculation arises because the same primary event may occur in several places in a fault tree meaning the component probabilities in some cases are not independent. If the minimal cut sets are denoted as M_1, M_2, ..., M_n, then the constructed fault tree is logically equivalent to the expression $T = M_1 \cup M_2 \cup \ldots \cup M_n$. This expression need to be evaluated, but bearing in mind, the minimal cut sets are neither mutually exclusive nor independent. So, the general expression for the probability of n arbitrary events is:

$$P(M_1 \cup M_2 \cup \ldots \cup M_n) = \sum_{i=1}^{n} P(M_i) - \sum_{i=2}^{n} \sum_{j=1}^{i-1} P\left(M_i \cap M_j\right) + \\ + \sum_{i=3}^{n} \sum_{j=2}^{i-1} \sum_{k=1}^{j-1} P\left(M_i \cap M_j \cap M_k\right) - \cdots \\ + (-1)^{n-1} P\left(M_i \cap M_j \cap \ldots \cap M_r\right) \qquad (1)$$

This formula presents the sum of terms each of which is the probability of the *q-th* order ($q = 2, 3, \ldots, r$) of minimal cut sets. The probability of multiple order minimal cut sets cannot be considered as the simple product of their individual probabilities. If it is supposed that the primary events are independent, then the product of the probabilities of all the primary (or undeveloped) events that occur in any cut set, can take each term exactly once. As this series has $2N$ terms (N denotes the number of minimal cut sets), this kind of calculation can take an unacceptable long time to evaluate all possible terms in this series, even for fairly small FTA. Fortunately, it is not necessary to compute all possible terms, so it is used to apply the next approximation:

$$P_T \approx \sum_{i=1}^{n} P(M_1); \; P_T \approx P_1 - \sum_{i=2}^{n} \sum_{j=1}^{i-1} P\left(M_1 \cap M_2\right); \\ P_T \approx P_2 - \sum_{i=3}^{n} \sum_{j=2}^{i-1} \sum_{k=1}^{j-1} (M_1 \cap M_2 \cap M_3) \ldots \qquad (2)$$

The first term presents simple sum of probabilities of the first order minimal cut sets. The increments in the series alternate the sign, so it presents an upper bound, then the second presents a lower bound, and then again the third term improved upper bound, etc.

CASE STADY: DERAILMENTS ON RAILWAY IN SERBIA

The model is formed by using a standard fault tree. In the first phase, the construction of fault tree was carried out using established scenarios based on which the qualitative analysis was done. In the next phase the quantification of fault tree was done by determining the probability of basic and undeveloped events. These probabilities were derived from an analysis of accident data that have occurred in the three-year period from 2012 - 2014. on the Serbian railway network. There were 312 derailments of all accidents during this period.

Developing the model was based on the recommendations of the ERA, according to which the derailments, by cause, is divided into three basic categories: derailments caused by failures of the infrastructure facilities (branch B1 in Figure 1), derailments occurred as a result of failures in the rolling stock (branch B2 in Figure 2) and derailments caused by errors railway staff made during operational work and intentional acts of third parties (branch B3 in Figure 3). The branches B1, B2 and B3 are associated with the top event by OR logic gate

Table 1 shows the basic and undeveloped events of the fault tree, constructed for the considered accidents problem of derailments. For each of the events, there are given the data code, short description and assigned probability calculated on the basis of the sample. It can be seen there are a total of 57 events, of which 40 of them belong to the basic events, 16 events (shaded in the table 1) are undeveloped events. Also, there is one conditional event (denoted as D26) which refers to cases the wagons are on the loading and unloading operations.

Table 2 contains data codes and a brief description of the intermediate events appeared in the model.

Table 1. The basic and undeveloped events used in FTA

No.	**Label**	**Event**	**Probability**	**No.**	**Label**	**Event**	**Probability**
1	D1	Subsidence	0.0018265	30	E20	Other failures of wheels	0.0009132

No.	Label	Event	Probability	No.	Label	Event	Probability
2	D2	Earth slide (leading to derailment not collision)	0.0009132	31	E21	Breakage of bogie structure parts	0.0009132
3	D3	Washing out substructure due to flood or hard rains	0.0027397	32	E22	The effects of bogie stiffness in curved track	0.0036530
4	D13	Twisted and breakage of wagon structures (frames)	0.0018265	33	E23	Other failures of bogies	0.0036530
5	D14	Too high twist stiffness in relation to length of wagon	0.0009132	34	E24	Breakage of springs in the bogie suspension	0.0018265
6	D15	Railway brake insert detrition	0.0009132	35	E25	Other failures of the suspension system in bogie	0.0009132
7	D16	Railway brake insert blockage	0.0009132	36	E26	Emty and light wagons before heavy and loaded wagons	0.0018265
8	D17	Other mulfunction of railway brakes	0.0009132	37	E27	The number of wagons with defective brakes are greater then allowed	0.0009132
9	D20	Brakes not correct set with respect to load or speed of brake application	0.0045662	38	E28	Wagon is overloaded	0.0036530

No.	Label	Event	Probability	No.	Label	Event	Probability
		(wrong choice of braking force)					
10	D21	Brakes not properly checked and tested	0.0082192	39	E29	Wagon is unevenly loaded	0.0036530
11	D23	Point switched to new position while point is occupied by train	0.0127854	40	E30	Insufficient fasten and secured load on wagon	0.0027397
12	D26	Wagon is located on loading place or in shunting	0.3000000	41	E31	Other irregularity with load	0.0009132
13	E1	Unscrewed or removed screw spikes	0.0045662	42	E34	Engine driver breakes the speed limit due to bad communication	0.0118721
14	E2	Removed or breakege of rail support and fastening parts and ties	0.0063927	43	E35	Engine driver breakes the speed limit due to any other reason	0.0063927
15	E5	Failures of switch point rails	0.0036530	44	E37	improper braking (stopping) wagns (brake block)	0.0073059
16	E6	irregular track gauge of switch (greater or less of standard)	0.0054795	45	F1	Rupture of rails	0.0109589
17	E7	Blockage of	0.0027397	46	F2	too heavy rail	0.0073059

No.	Label	Event	Probability	No.	Label	Event	Probability
		switch point rails due to ice or rusty parts				detrition	
18	E8	Other failures of switches	0.0009132	47	F3	Too geasy rails	0.0036530
19	E9	Existing sun kinks	0.0054795	48	F4	Rotting sleepers	0.0146119
20	E10	irregular track gauge (greater or less of standard)	0.0100457	49	F5	Damage of concrete sleepers	0.0082192
21	E11	Irregular rail hight on curved railway track	0.0063927	50	F7	The train running into another train located on the railway track	0.0063927
22	E12	Other failures on railway tracks	0.0018265	51	F8	Worker accidently set the switch in incorrect position (switch point in intermediate position)	0.0127854
23	E13	Parts or goods fell out from wagons	0.0036530	52	F9	The switch is in the incorrect position by an act of third party	0.0073059
24	E14	Large quantity of snow and ice	0.0127854	53	F11	Improper stopping wagons (using brake block)	0.0118721
25	E15	Mudslide	0.0027397	54	G1	Railway staff accidently set the switch in	0.0100457

No.	Label	Event	Probability	No.	Label	Event	Probability
						wrong way	
26	E16	Rupture of the axle shaft in bogie	0.0054795	55	G2	The switch is wrong position by act of the third party	0.0109589
27	E17	Rupture of the wheel bearing	0.0018265	56	G3	Improper movig wagons from loading place by professional stuf	0.0082192
28	E18	Detrition of the railway wheel flange	0.0027397	57	G4	Improper movig wagons from loading place by third party	0.0063927
29	E19	Irregular of the railway wheel profile	0.0018265				

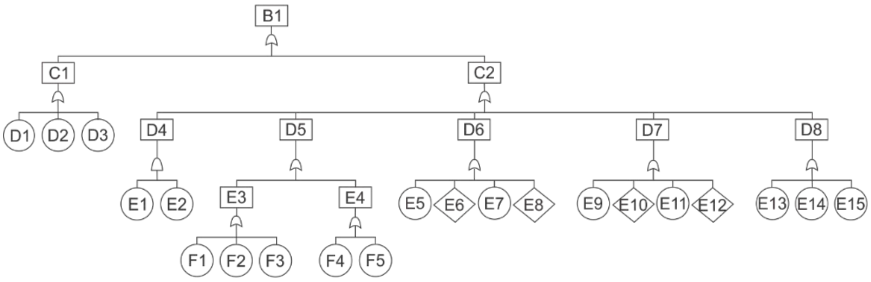

Fig. 1. The branch B1 of the fault tree

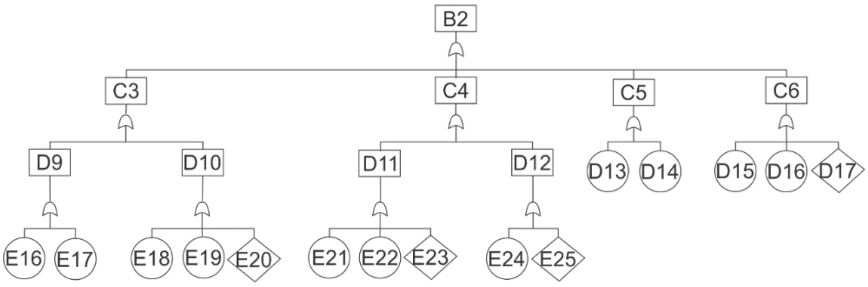

Fig. 2. The branch B2 of the fault tree

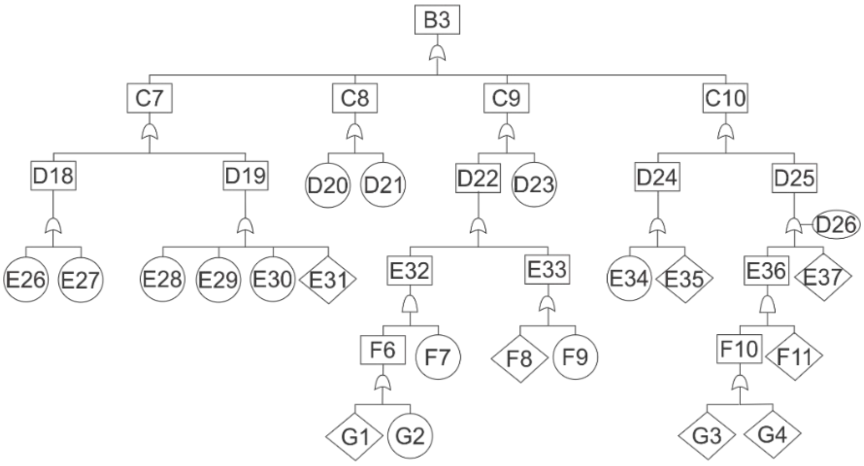

Fig. 3. The branch B3 of the fault tree

Table 2. The intermediate events used in FTA

No.	Label	Event
1	A	Derailment
2	B1	Derailment caused by infrastructure failures
3	B2	Derailment caused by rolling stock failures
4	B3	Derailment caused by human failures
5	C1	Infrastructure failures comprising substructure failures
6	C2	Infrastructure failures comprising superstructure failures
7	C3	wheel failures and failures of the axle box and axle shaft
8	C4	Bogie failures
9	C5	Wagon structure (frame) failures
10	C6	Brakes failures
11	C7	Derailment caused by unfavorable train composition
12	C8	Derailment caused by irregularities of braking procedures
13	C9	Derailment caused by irregular switch handling
14	C10	Derailment caused by breaking the speed limit

No.	Label	Event
15	D4	Rail support and fastening failures of railway tracks and switches
16	D5	Failures of railway sleepers and rail tracks
17	D6	Breakage of movable and unmovable parts of switches
18	D7	Deviation of standard track gauge
19	D8	Obstructions on railway tracks
20	D9	Failures of railway axle set
21	D10	Failures of railway wheels
22	D11	Structural failures of bogies
23	D12	Failures of bogie suspensions
24	D18	Unfavorable train composition (empties before loaded wagons)
25	D19	Irregularity of wagon loading
26	D22	The switch is set in wrong way or incorrect position (intermediate position of swith point rails)
27	D24	Speed limit breaking by engine driver's fault
28	D25	Speed limit breaking caused by workers or third party
29	E3	Superstructure failures comprising rail failures
30	E4	superstructure failures comprising frazzle and failures of sleepers
31	E32	The switch is set in wrong position (straight and diverging track)
32	E33	The switch is incorrect position (switch point rail is in intermediate position)
33	E36	improper moving wagons from the loading space
34	F6	The switch is set in wrong way by human error
35	F10	Improper move the wagon from the loading place by unprofessional staff

RESULT

The fault tree constructed on this way contains 53 cut sets, of which 47 are single component section, but 6 of them belong to the class of multicomponent cut sets. In analyzing, cut sets with higher probability are more significant compared to cut sets with low probability. It is usually single component cut sets are with higher probability, because with multicomponent cut sets it is necessary that all events realized.

The probability of top event is calculated in 5 iterations and asymptotically approaching to the value of $1.943 \cdot 10^{-1}$. Participation of individual unwanted events defined in the scenarios lead to the top event and whose realization inevitably leads to derailment is presented in Table 3.

Table 3. The cut sets and its participation in scenarios of FTA

No	**Label**	**Probability**	**Contribution**	**No**	**Label**	**Probability**	**Contribution**
1	D1	1.8265E-03	0.94%	30	E25	9.1320E-04	0.47%
2	D13	1.8265E-03	0.94%	31	E26	1.8265E-03	0.94%
3	D14	9.1320E-04	0.47%	32	E27	9.1320E-04	0.47%
4	D15	9.1320E-04	0.47%	33	E28	3.6530E-03	1.88%
5	D16	9.1320E-04	0.47%	34	E29	3.6530E-03	1.88%
6	D17	9.1320E-04	0.47%	35	E30	2.7397E-03	1.41%
7	D2	9.1320E-04	0.47%	36	E31	9.1320E-04	0.47%
8	D20	4.5662E-03	2.35%	37	E34	1.1872E-02	6.11%
9	D21	8.2192E-03	4.23%	38	E35	6.3927E-03	3.29%
10	D23	1.2785E-02	6.58%	39	E37	2.1918E-03	1.13%
11	D26	2.2438E-03	1.15%	40	E5	3.6530E-03	1.88%
12	D3	2.7397E-03	1.41%	41	E6	5.4795E-03	2.82%
13	E1	2.9190E-05	0.02%	42	E7	2.7397E-03	1.41%
14	E10	1.0046E-02	5.17%	43	E8	9.1320E-04	0.47%
15	E11	6.3927E-03	3.29%	44	E9	5.4795E-03	2.82%
16	E12	1.8265E-03	0.94%	45	F1	1.0959E-02	5.64%
17	E13	3.6530E-03	1.88%	46	F11	5.2042E-05	0.03%
18	E14	1.2786E-02	6.58%	47	F2	7.3059E-03	3.76%
19	E15	2.7397E-03	1.41%	48	F3	3.6530E-03	1.88%

No	**Label**	**Probability**	**Contribution**	**No**	**Label**	**Probability**	**Contribution**
20	E16	5.4795E-03	2.82%	49	F4	1.4612E-02	7.52%
21	E17	1.8265E-03	0.94%	50	F5	8.2192E-03	4.23%
22	E18	2.7397E-03	1.41%	51	F7	1.3428E-04	0.07%
23	E19	1.8265E-03	0.94%	52	F8	1.2785E-02	6.58%
24	E2	2.9190E-05	0.02%	53	F9	7.3059E-03	3.76%
25	E20	9.1320E-04	0.47%	54	G1	6.4219E-05	0.03%
26	E21	9.1320E-04	0.47%	55	G2	7.0057E-05	0.04%
27	E22	3.6530E-03	1.88%	56	G3	2.9274E-05	0.02%
28	E23	3.6530E-03	1.88%	57	G4	2.2768E-05	0.01%
29	E24	1.8265E-03	0.94%				

Considered the table 3, it can be seen that the largest influence to derailments on the Serbian railways network has the event labeled as F4 (rotten sleepers), with a participation of 7.52%. Point switched to new position while point is occupied by train, switches mounted in the wrong direction and the occurrence of snow and ice are following with a participation of 6.58%.

CONCLUSION

Analysis of railway accidents happened on the territory of the Republic of Serbia in the period from 2012. – 2014. shows that the derailments make a significant number of accidents in the total number of accidents of all kinds during this period.

The aim of this paper was to form a model for determination the probability of derailment on the Serbian Railways, and to identify scenarios that will lead to it. On the other hand, it is necessary to determine what events precede the occurrence of derailments. For this purpose, it was used FTA as the most appropriate method.

The analysis found that the most common causes of derailment on the railways in Serbia are bad state (rotten) sleepers and errors made by railway staff during handling with switches. In order to reduce the number of events cause derailments, it is necessary to take measures which include better maintenance of railroad (especially superstructure) and railway staffs' responsibility in their service. Measures could be undertaken to make better maintenance of railroads and rail superstructure should include establishing the strategy and rationalization of finance invested in these activities and reconstruction of the railway of higher rank that are in bad condition. As for the staff, measures that would affect the reduction of the derailment occurrences imply activities to improve knowledge and training of staff, as well more frequent examinations and testing.

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