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Use of automatic signalling system for reduction of the risk of transportation incidents in railway stations[1]

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Abstract. Aim. *Evaluating the risk of collision between trains during shunting operations in railway stations. Risk is the combination of the probability and consequences of an event. The most complicated task related to risk assessment is the choice of the evaluation model for the probability of an undesired event. The model must ensure practical applicability of the results. In the context of railway facilities the construction of analytical models of probability evaluation is of principal interest due to the possibility to demonstrate the factors that are taken into consideration by the model. The main purpose of this paper is to examine the extent to which the Shunting Automatic Cab Signalling System (MALS) contributes to the probability of side collision of trains involving shunting engines in railway stations. The main function of the Shunting Automatic Cab Signalling System is to ensure that shunting engines do not pass signals at danger in stations.* **Methods.** *Methods of the probability theory and theory of random processes, addition, multiplication formulas, composite probability, properties of Poisson flows. In [2] a method is suggested for calculating the probability of collision as the result of shunting or train locomotive passing a signal at danger. The development of the method was based on the main assumption that the flow of shunting consists for each switch is a Poisson flow. This paper suggests a modification of this method that takes into consideration the possible use of the MALS system with shunting engines. The input data for the algorithm of calculation of the collision probability are the station topology, passenger train schedule and their possible routes through the station, average train lengths and speeds, as well as the frequency of shunting consists passing over switches.*

Results. *An algorithm has been developed for calculation of the probability of train-to-train collision involving shunting engines within a random time period. For different operating modes, e.g. pulling up, coupling, formulas are shown for calculation of the probability of collision with a passenger or freight train on a random switch. The algorithms consists in the following: 1) a time period is specified for which it is required to calculate the probability of collision; 2) passenger train timetable is designed using data from ASU "Express"; 3) overall number of passenger trains passing through the station within the specified time period is calculated; 4) passenger trains are renumbered according to the order of their arrival to the station; 5) probability of signal violation by shunting engine driver is calculated; 6) probability of violation of traffic safety by shunting engine driver in the "pull up" mode is calculated; 7) probability of violation of traffic safety by the shunting engine driver after coupling with the "coupling" mode off is calculated; 8) overall number of possible routes for each train is calculated; 9) for each train the frequency of one or another route is identified; 10) for each switch of each route a number is specified in the order of appearance; 11) probability that each passenger train on each route has at least one collision is calculated; 12) probability of at least one collision of each passenger train moving through the station is calculated; 13) probability of at least one collision in the station within the specified period of time is calculated. The paper considers the example of calculation of collision probability for an individual train route and the station as a whole within a month and a year. It shows that the use of MALS helps significantly reduce the probability of side collisions in railway stations.*

Keywords: *railway transportation, traffic safety, shunting operations, probability of collision.*

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1. Introduction

Both passenger and freight traffic of certain density may be affected by various adverse events that may cause reputational and material costs to JSC RZD associated, for instance, with damage to infrastructure and/or rolling stock. Therefore, in order to identify quantitative characteristics of the hazard of one or another event the concept of risk is introduced that according to [1] is the functional of the probability and damage from the adverse event.

As noted in [2], during shunting operations in stations signal violations by one of the vehicles may cause not only collisions between two shunting consists, but particularly between a passenger train and a shunting consists, which as it is shown in [3] may cause loss of life and consequently significant damage. Despite the fact that in case of a single passenger train passing through a station the probability of its collision with a shunting consist is quite low, the probability of at least one collision per year per all the trains passing through a station is a significant value, especially if the stations feature intense shunting operations. The installation and use of the MALS system may help reduce the probability of collision between trains.

The installation of MALS on shunting engines enables several movement modes. The first one is the "typical" mode, in which MALS operates normally. The second one is the "pull up" mode, in which MALS is disabled and the shunting engine driver can drive the train closer than 20 meters to a restrictive signal and consequently may pass the restrictive signal, which may cause a collision between a shunting consist and a passenger or freight train. The third one is the "movement after coupling with the "coupling" mode off, in which when moving with the wagons in front of the engine MALS incorrectly determines the location of the head and tail of the consist, which may also cause signal violation. The second and third modes are abnormal. Obviously, most of the time a shunting engine is in the "typical" mode, yet in the other two modes the probability of signal violation is much higher, therefore each of those cases is characterized by its own probability of collision between a shunting consist with a passenger/freight train and is individually examined in this paper.

2. An algorithm for calculation of the probability of collision within a random time period if the MALS system is used

Let us introduce the following designations:

N is the total number of switches in the station;

L is the number of shunting engines;

N_l is the number of switches passed by shunting consist per hour, l=1,…L;

r_l is the number of half-runs, l=1,…L;

s_l is the number of couplings with the "coupling" mode off, l=1,…L;

T_l is the number of pull ups, l=1,…L;

l_{sh} is the average length of shunting consist;

l_p is the average length of passenger train;

v_p is the average speed of passenger train movement through the station;

v_{sh} is the average speed of shunting consist movement through the station;

v_{pu} is the average speed of shunting consist movement through the station in the "pull up" mode;

P_p is the probability of passenger train violating a restrictive signal;

$P_{sh(one)}$ is the probability of violation of restrictive signal by shunting engine driver while operating without an assistant driver;

$P_{sh(two)}$ is the probability of violation of restrictive signal by shunting engine driver while operating with an assistant driver;

P_{two} is the probability of shunting engine being manned with driver and assistant driver;

P_{Wsh} is the probability of coupling with subsequent movement of shunting engine with wagons;

$P_O(s)$ is the probability of failure by the station duty officer to prevent a violation of restrictive signal in the "pull up" mode;

P_{PUE} is the probability of signal violation by a shunting engine driver in the "pull up" mode when the shunting engine is at the head of the train;

P_{PUT} is the probability of signal violation by a shunting engine driver in the "pull up" mode when the shunting engine is at the tail of the train;

P_{ShM} is the probability of traffic safety violation by the shunting master;

λ_S^i is the frequency of shunting consists stopping on switches that did not violate traffic safety while crossing the switch, i=1,…,N;

τ_S^i is the average time a shunting consist dwells on a switch that did not violate traffic safety while crossing the switch after having stopped on the switch i=1,…,N;

τ_{PU} is the average time it takes a shunting consist to clear a switch after entering it in the "pull up" mode after having stopped of the switch.

1. A time period T is specified, for which it is required to calculate the probability of collision. Passenger train timetable is retrieved from ASU Express. According to the timetable all passenger trains that moving trough the station within the time T are identified.

2. I is identified, i.e. the total number of passenger trains that move through the station within the time T.

3. Passenger trains moving through the station within the considered time are numbered according to the time of their arrival to the station. Passenger trains are renumbered according to the order of their arrival to the station, i.e. the first arrived train is numbered 1, the second is numbered 2 and so on.

4. The probability of signal violation by shunting engine driver is calculated using the formula

$$P_{Sh} = P_{TWO} \cdot P_{SH(TWO)} + \left(1 - P_{TWO}\right) \cdot P_{Sh(TWO)},$$

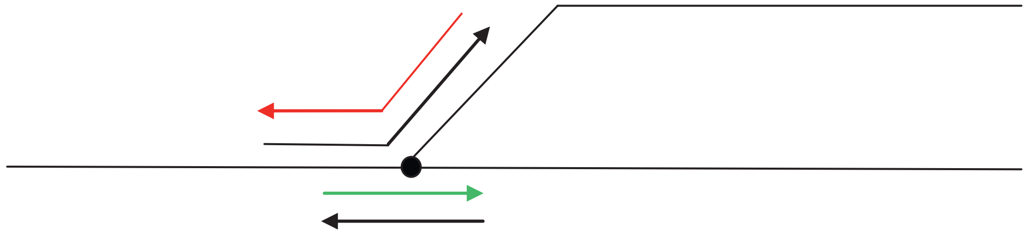

Figure 1. Movement direction (red arrow) of shunting consist across a switch (circle) that makes possible a collision with a passenger train moving in the direction shown with the green arrow

the probability of traffic safety violation by shunting engine driver in the "pull up" mode is calculated using the formula

$$P_{\text{PU}} = \frac{1}{2} P_{\text{O}}(s)(P_{\text{PUE}} + P_{\text{PUT}}),$$

the probability of traffic safety violation by shunting engine driver after coupling with the "coupling" mode off is calculated using the formula

$$P_{\text{Cu}} = \left(1 - \frac{1}{2} P_{\text{WSh}}\right) P_{\text{Sh}} + \frac{1}{2} P_{\text{Sh}} P_{\text{ShM}}.$$

The following is calculated for each switch

$\tilde{\lambda}_{\text{PU}}$, frequency of shunting consist in "pull up" mode being before a switch

$$\tilde{\lambda}_{\text{PU}} = \sum_{l=1}^{L} \frac{1}{N} \cdot \frac{T_l}{24};$$

$\tilde{\lambda}_{\text{Cu}}$, the frequency of a switch being crossed by a shunting consist after coupling with the "coupling" mode off

$$\tilde{\lambda}_{\text{Cu}} = \sum_{l=1}^{L} \frac{N_l}{N} \cdot \frac{s_l}{r_l};$$

$\tilde{\lambda}_{\text{Sh}}$, the frequency of a switch being crossed by a shunting consist in "normal" mode

$$\tilde{\lambda}_{\text{Sh}} = \sum_{l=1}^{L} \frac{N_l}{N} - \tilde{\lambda}_{\text{PU}} P_{\text{PU}} - \tilde{\lambda}_{\text{Cu}}.$$

The frequency[1] λ^1_{PU} of a switch being possibly crossed by a shunting consist in "pull up" mode in a certain direction l is calculated using formula $\lambda^1_{\text{PU}} = \tilde{\lambda}_{\text{PU}} / 4$.

The frequency λ^1_{Cu} of a switch being crossed by a shunting consist after coupling with the "coupling" mode off in a certain direction l is calculated using the formula $\lambda^1_{\text{Cu}} = \tilde{\lambda}_{\text{Cu}} / 4$.

The frequency λ^1_{Sh} of a switch being crossed by a shunting consist in the "normal" mode in a certain direction l is calculated using formula $\lambda^1_{\text{Sh}} = \tilde{\lambda}_{\text{Sh}} / 4$.

5. The value *i* is assumed to equal to one.

6. We calculate *K*, the total number of possible routes for the *i*-th train.

7. The value *k* is assumed to equal to one.

[1] The frequencies can be specified during data collection for each switch in the considered station.

8. For the *i*-th train the frequency of using one or another routes is calculated[2]

$$P(R_k) = \frac{m_{R_k}}{n},$$

where m_{R_k} is the number of trains with the number *i* that took the route R_k, while *n* is the total number of passenger trains with the number *i*, that moved across the station over the observation period.

9. When the route R_k is processed, the included switches are numbered in the order the *i*th train passes them, i.e. the first switch passed by a passenger train is numbered 1, the second switch passed by the passenger train is numbered 2 and so on. Let *m* be the total number of switches that the *i*-th train crosses on the route R_k.

10. The value *j* is assumed to equal to one.

11. If the *j*-th switch of the route R_k of the *i*-th passenger train is uninsulated[3], the following are identified:

λ_{Sh} is the frequency of shunting consist crossing a switch in "normal" mode in a direction that makes a collision possible (selected out of λ^1_{Sh} obtained at step 4, see Figure 1);

λ_{Cu} is the frequency of passing by a shunting consist with a shunting engine that performed the coupling with the "coupling" mode off of a switch in a direction that makes a collision possible (selected from λ^1_{Cu} obtained at step 4, see Figure 1);

λ_{PU} is the frequency of possible passing by a shunting consist with a shunting engine that was before the switch in the "pull up" mode of a switch in a direction that makes a collision possible (selected from λ^1_{PU} obtained at step 4, see Figure 1);

λ_{S} is the frequency of shunting consists stopping on the *j*-th switch

τ_{S} is the average time a shunting consist dwells on the *j*-th switch if it stops on it;

P_{PS} is the probability of the *i*-th passenger train stopping on the *j*-th switch;

τ_{PS} is the average time the *i*-th passenger train dwells on the *j*-th switch;

[2] If there is no data on the previous transits of trains across the station, all routes are assumed to be equally possible, i.e. for any *k* the probability $P(R_k)$ of using the route R_k is calculated using formula $P(R_k) = 1/K$.

[3] An insulated switch is a switch, on which a collision caused by signal violation is impossible, while an uninsulated switch is one on which a collision is possible.

the probability of collision through a fault of the shunting engine driver (in case of MALS failure) who violated a signal

$$P_{Sh}(A_{\text{Sh}}) = \lambda_{\text{Sh}} P_{\text{Sh}} \left(\frac{l_{\text{P}}}{v_{\text{P}}} + \frac{l_{\text{Sh}}}{v_{\text{Sh}}} + P_{\text{PS}} \tau_{\text{PS пс}} \right);$$

the probability of collision through a fault of the passenger train driver who violated a signal

$$P_{Sh}(A_{\text{P}}) = P_{\text{P}} \lambda_{\text{Sh}} \left(\frac{l_{\text{Sh}}}{v_{\text{Sh}}} + \frac{l_{\text{P}}}{v_{\text{P}}} \right) + P_{\text{P}} \lambda_{\text{Cu}} \left(\frac{l_{\text{Sh}}}{v_{\text{Sh}}} + \frac{l_{\text{P}}}{v_{\text{P}}} \right);$$

the probability of collision through a fault of the passenger train driver who violated a signal and allowed the train's collision with wagons dwelling on a switch

$$P_{Sh}(A_{\text{S}}) = P_{\text{P}} \lambda_{\text{S}} \tau_{\text{S}};$$

the probability of collision through a fault of the shunting engine driver who violated a signal in the "pull up" mode

$$P_{Sh}(A_{\text{PU}}) = \lambda_{\text{PU}} P_{\text{PU}} \left(\frac{l_{\text{P}}}{v_{\text{P}}} + \frac{l_{\text{PU}}}{v_{\text{PU}}} + P_{\text{PS}} \tau_{\text{PS}} + \tau_{\text{PU}} \right);$$

the probability of collision caused by signal violation by both the shunting engine and passenger train drivers

$$P_{Sh}(A_{\text{PUP}}) = \lambda_{\text{PU}} P_{\text{PU}} P_{\text{PU}} \left(\frac{l_{\text{PU}}}{v_{\text{PU}}} + \frac{l_{\text{P}}}{v_{\text{P}}} \right) +$$
$$+ \lambda_{\text{Sh}} P_{\text{Sh}} P_{\text{P}} \left(\frac{l_{\text{P}}}{v_{\text{P}}} + \frac{l_{\text{Sh}}}{v_{\text{Sh}}} \right) + \lambda_{\text{Cu}} P_{\text{Cu}} P_{\text{P}} \left(\frac{l_{\text{P}}}{v_{\text{P}}} + \frac{l_{\text{Sh}}}{v_{\text{Sh}}} \right);$$

the probability of collision through a fault of the shunting engine driver after coupling with the "coupling" mode off

$$P_{Sh}(A_{\text{Cu}}) = \lambda_{\text{Cu}} P_{\text{Cu}} \left(\frac{l_{\text{P}}}{v_{\text{P}}} + \frac{l_{\text{Sh}}}{v_{\text{Sh}}} + P_{\text{PS}} \tau_{\text{PS}} \right).$$

The resultant probability of collision on the *j*-th switch is calculated using the formula

$$P_{Sh}(A_{k:j}) = \Bigg(\lambda_{\text{Sh}} \left(\frac{l_{\text{P}}}{v_{\text{P}}} + \frac{l_{\text{Sh}}}{v_{\text{Sh}}} \right) (P_{\text{Sh}}(1+P_{\text{P}}) + P_{\text{P}}) +$$
$$+ \lambda_{\text{Cu}} \left(\frac{l_{\text{P}}}{v_{\text{P}}} + \frac{l_{\text{Sh}}}{v_{\text{Sh}}} \right) (P_{\text{Cu}}(1+P_{\text{P}}) + P_{\text{P}}) +$$
$$+ \lambda_{\text{PU}} \left(\frac{l_{\text{PU}}}{v_{\text{PU}}} + \frac{l_{\text{P}}}{v_{\text{P}}} + \tau_{\text{PU}} \right) P_{\text{PU}}(1+P_{\text{P}}) + \lambda_{\text{S}} P_{\text{P}} \tau_{\text{S}} +$$
$$+ \left(\lambda_{\text{Sh}} P_{\text{Sh}} + \lambda_{\text{PU}} P_{\text{PU}} + \lambda_{\text{Cu}} P_{\text{Cu}} \right) P_{\text{PS}} \tau_{\text{PS}} \Bigg) \cdot k_{\text{S}},$$

where k_{S} takes on the value 1 if the switch is uninsulated, and 0 if it is insulated, while the other variables in the formula are defined at steps 1 and 4.

12. If *j*=*m*, proceed to step 14, otherwise proceed to step 13.

13. *j*:=*j*+1, proceed to step 11.

14. We calculate the probability that the *i*-th passenger train on route R_k has at least one collision that amounts to

$$P_{Sh}(A_i \mid R_k) = 1 - \prod_{j=1}^{m} (1 - P_{Sh}(A_{k:j})),$$

Table 1. Data unit describing the station topology and shunting operations in it

Name	Notation	Number	Measurement units
Total number of switches in the station	N	102	pcs
Number of shunting engines	L	2	pcs
Number of switches passed by shunting consist per hour with engine no. 1	N_1	36	pcs
Number of switches passed by shunting consist per hour with engine no. 2	N_2	36	pcs
Average length of shunting consist	l_{Sh}	0,2	km
Average speed of shunting consist movement through the station	v_{Sh}	4,2	km/h
Probability of violation of restrictive signal by shunting engine driver while operating without an assistant driver	$P_{\text{Sh(one)}}$	$2{,}1 \cdot 10^{-8}$	
Probability of violation of restrictive signal by shunting engine driver while operating with an assistant driver	$P_{\text{Sh(two)}}$	$7 \cdot 10^{-9}$	
Probability of shunting engine being manned with driver and assistant driver	P_{two}	0,8	
Frequency of shunting consists stopping on switches that did not violate traffic safety while crossing the switch	λ_{S}^{1}, ..., λ_{S}^{102}	0, ... 0	1/h, ..., 1/h
Average time a shunting consist dwells on a switch that did not violate traffic safety while crossing the switch after having stopped on the switch	τ_{S}^{1}, ..., τ_{S}^{102}	0, ... 0	h, ..., h

where the probabilities $P_{Sh}(A_{k,j})$ were calculated at step 11, the value m was calculated at step 9.

15. If $k=K$, proceed to step 17, otherwise proceed to step 16.

16. $k:=k+1$, proceed to step 8.

17. We calculate the probability of at least one collision involving passenger train no. i while moving through the station

$$P_{Sh}(A_i) = \sum_{k=1}^{K} P_{Sh}(A_i \mid R_k) P(R_k),$$

where the probabilities $P_{Sh}(A_i|R_k)$ were calculated at step 14, the probabilities $P(R_k)$ were calculated at step 8, the value K was calculated at step 6.

18. If $i=I$, proceed to step 20, otherwise proceed to step 19.

19. $i:=i+1$, proceed to step 6.

20. We calculate the probability of at least one collision within the time period T

$$P_{Sh}(A_{PU}) = P_{Sh}(A_1 + A_2 + \ldots + A_I) = 1 - \prod_{i=1}^{I}(1 - P_{Sh}(A_i)).$$

3. An example of calculation of the probability of collision between a passenger train and a shunting consist for some stations equipped with the MALS system

Let there be 4 possible movement directions from and to the station (station layout is shown in Figure 2): northeast, southeast, northwest, southwest. From the northeast trains arrive to the station via track F, from the southeast the trains arrive to the station via track D, from the northwest the trains arrive to the station via track B, from the southwest the trains arrive to the station via track B or track C. From the station, the northwest is accessed via track F, the southeast is accessed via track E, the northwest is accessed via track A, the southwest is accessed via track B or C. Let the commuter trains be able to stop only on tracks 1, 3, 7, 8, 11, 12, 13, while the long distance passenger and freight trains be able to stop or move through the station only via tracks 1, 3, 4, 5, 6, 7, 8. Let us assume that we have the train timetable for May and August. Let us fill in the table with data required for the application of probability calculation algorithm.

Let us consider passenger train no. 255N that passes through the station without stopping from northeast to northwest. It is known that this train will be directed to the first track. In this case it only has 6 routes through the station.

Let us calculate the probability of signal violation by a shunting consist, that depends on the probability P_{two} of the driver and assistant driver being onboard the engine, as well as the probabilities $P_{Sh(two)}$ and $P_{Sh(one)}$ that the shunting

Table 2. Additional data unit describing the station topology and shunting operations in it

Name	Notation	Number	Measurement units
Number of half-runs performed by engine no. 1	r_1	20	pcs
Number of half-runs performed by engine no. 2	r_2	22	pcs
Number of couplings with the «coupling» mode off performed by engine no. 1	s_1	2	pcs
Number of couplings with the «coupling» mode off performed by engine no. 2	s_2	0	pcs
Number of pull ups performed by engine no. 1	T_1	3	pcs
Number of pull ups performed by engine no. 2	T_2	3	pcs
Length of shunting engine (wagon)	l_{PU}	0,2	km
Average speed of shunting consist movement through the station in the «pull up» mode	v_{PU}	2	km/h
Average time it takes a shunting consist to clear a switch after entering it in the «pull up» mode after having stopped of the switch	τ_{PU}	0,01	h
Probability of coupling with subsequent movement of shunting engine with wagons	P_{WSh}	0,25	
Probability of failure by the station duty officer to prevent a violation of restrictive signal in the «pull up» mode	$P_O^1(s)$	10^{-2}	
Probability of signal violation by a shunting engine driver in the «pull up» mode when the shunting engine is at the head of the train	P_{PUE}	10^{-4}	
Probability of signal violation by a shunting engine driver in the «pull up» mode when the shunting engine is at the tail of the train	P_{PUT}	10^{-3}	
Probability of traffic safety violation by the shunting master	P_{ShM}	10^{-3}	

consist crosses a switch at danger, while the driver and assistant driver or only the driver is in the cab (see item 4 of the algorithm)

$$P_{Sh} = P_{two} \cdot P_{Sh(two)} + (1 - P_{two}) \cdot P_{Sh(one)} = \\ = 0,8 \cdot 7 \cdot 10^{-9} + (1-0,8) \cdot 2,1 \cdot 10^{-8} \approx 10^{-8}.$$

The probability of traffic safety violation by a shunting engine driver in the "pull up" mode equals to (see item 4 of the algorithm)

$$P_{PU} = \frac{1}{2} P_O(s)(P_{PUE} + P_{PUT}) = \\ = \frac{1}{2} \cdot 10^{-2} \cdot (10^{-4} + 10^{-3}) = 5,5 \cdot 10^{-6},$$

the probability of traffic safety violation by a shunting engine driver after coupling with the "coupling" mode off equals to (see item 4 of the algorithm)

$$P_{CU} = \left(1 - \frac{1}{2} P_{WSh}\right) P_{Sh} + \frac{1}{2} P_{WSh} P_{ShM} = \\ = \left(1 - \frac{1}{2} \cdot \frac{1}{4}\right) \cdot 10^{-8} + \frac{1}{2} \cdot \frac{1}{4} \cdot 10^{-3} \approx 1,25 \cdot 10^{-4}.$$

Frequency of shunting consist in "pull up" mode being before a random switch equals to (see item 4 of the algorithm)

$$\tilde{\lambda}_{PU} = \sum_{l=1}^{L} \frac{1}{N} \cdot \frac{T_l}{24} = \frac{1}{102} \cdot \frac{3}{24} + \frac{1}{102} \cdot \frac{3}{24} = 0,0025 \text{ (1/h)},$$

the frequency of random switch being crossed by a shunting consist after coupling with the "coupling" mode off equals to (see item 4 of the algorithm)

$$\tilde{\lambda}_{CU} = \sum_{l=1}^{L} \frac{N_l}{N} \cdot \frac{s_l}{r_l} = \frac{36}{102} \cdot \frac{2}{20} + \frac{36}{102} \cdot \frac{0}{22} = 0,035,$$

the frequency of a switch being crossed by a shunting consist in "normal" mode equals to (see item 4 of the algorithm)

$$\tilde{\lambda}_{Sh} == \sum_{l=1}^{L} \frac{N_l}{N} - \tilde{\lambda}_{PU} P_{PU} - \tilde{\lambda}_{CU} = \frac{36}{102} + \frac{36}{102} - \\ -0,0025 \cdot 5,5 \cdot 10^{-6} - 0,035 = 0,671.$$

Let us calculate the probability of at least one collision on route R_1. The probability $P(R_1)$ of the use of a route R_1 equals to (see item 8 if the algorithm)

$$P(R_1) = \frac{2}{2+1+0+0+0+0} = \frac{2}{3}.$$

Let us number the switches according to the order in which they are crossed by the train (see item 9 of the algorithm): 115→1, 121→2, 151-147→3, 149-161→4, 244→5, 238→6, 236→7, 174→8, 164→9, 154→10, 144→11, 138→12.

For switches nos. 144, 236, 149-161, 151-147 we have $\lambda_{Sh} = \tilde{\lambda}_{Sh} / 4 \approx 0,168$, $\lambda_{PU} = \tilde{\lambda}_{PU} / 4 \approx 0,0006$, $\lambda_{CU} = \tilde{\lambda}_{CU} / 4 \approx \approx 0,009$, where division by 4 is performed as each shunting consist can cross a switch in 4 possible directions (see Figure 1).

The probability of collision on non-insulated switches nos. 144, 236, 149-161, 151-147 is calculated using the formulas (see item 11 of the algorithm)

$$P_{Sh}(A_{1:3}) = \lambda_{Sh}\left(\frac{l_P}{v_P} + \frac{l_{Sh}}{v_{Sh}}\right)(P_{Sh}(1+P_P) + P_P) + \\ + \lambda_{CU}\left(\frac{l_P}{v_P} + \frac{l_{Sh}}{v_{Sh}}\right)(P_{CU}(1+P_P) + P_P) + \\ + \lambda_{PU}\left(\frac{l_P}{v_P} + \frac{l_{PU}}{v_{PU}} + \tau_{PU}\right) P_{PU}(1+P_P) + \lambda_S P_P \tau_S + \\ + (\lambda_{Sh} P_{Sh} + \lambda_{PU} P_{PU} + \lambda_{CU} P_{CU}) P_{PS} \tau_{PS} = \\ = 0,168 \cdot \left(\frac{0,48}{42} + \frac{0,2}{4,2}\right) \cdot (10^{-8} \cdot (1+10^{-7}) + 10^{-7}) + \\ + 0,009 \cdot \left(\frac{0,48}{42} + \frac{0,2}{4,2}\right) \cdot (1,25 \cdot 10^{-4} \cdot (1+10^{-7}) + 10^{-7}) + \\ + 0,0006 \cdot \left(\frac{0,48}{42} + \frac{0,02}{2} + 0,01\right) \cdot 5,5 \cdot 10^{-6} \cdot (1+10^{-7}) = 6,8 \cdot 10^{-8}.$$

$$P_{Sh}(A_{1:4}) = P_{Sh}(A_{1:7}) = P_{Sh}(A_{1:11}) = 0,168 \cdot \left(\frac{0,48}{42} + \frac{0,2}{4,2}\right) \cdot \\ \cdot (10^{-8} \cdot (1+10^{-7}) + 10^{-7}) + 0,009 \cdot \left(\frac{0,48}{42} + \frac{0,2}{4,2}\right) \cdot \\ \cdot (1,25 \cdot 10^{-4} \cdot (1+10^{-7}) + 10^{-7}) + 0,0006 \cdot \\ \cdot \left(\frac{0,48}{42} + \frac{0,02}{2} + 0,01\right) \cdot 5,5 \cdot 10^{-6} \cdot (1+10^{-7}) = 6,8 \cdot 10^{-8}.$$

For the insulated switches nos. 138, 154, 164, 174, 238, 244, 121, 115 the probability of collision equals to zero, i.e.

$$P_{Sh}(A_{1:1}) = P_{Sh}(A_{1:2}) = P_{Sh}(A_{1:5}) = P_{Sh}(A_{1:6}) = \\ = P_{Sh}(A_{1:8}) = P_{Sh}(A_{1:9}) = P_{Sh}(A_{1:10}) = P_{Sh}(A_{1:12}) = 0.$$

The probability of at least one collision involving passenger train no. 255N on route R_1 equals to (see item 14 of the algorithm)

$$P_{Sh}(A_1 \mid R_1) = 1 - 1 \cdot 1 \cdot (1 - 6,8 \cdot 10^{-8}) \cdot (1 - 6,8 \cdot 10^{-8}) \cdot \\ \cdot 1 \cdot 1 \cdot (1 - 6,8 \cdot 10^{-8}) \cdot 1 \cdot 1 \cdot 1 \cdot (1 - 6,8 \cdot 10^{-8}) \cdot 1 = 2,7 \cdot 10^{-7}.$$

Let us calculate the probability of at least one collision on route R_2. The probability $P(R_2)$ of the use of a route R_2 equals to (see item 8 if the algorithm)

$$P(R_2) = \frac{1}{2+1+0+0+0+0} = \frac{1}{3},$$

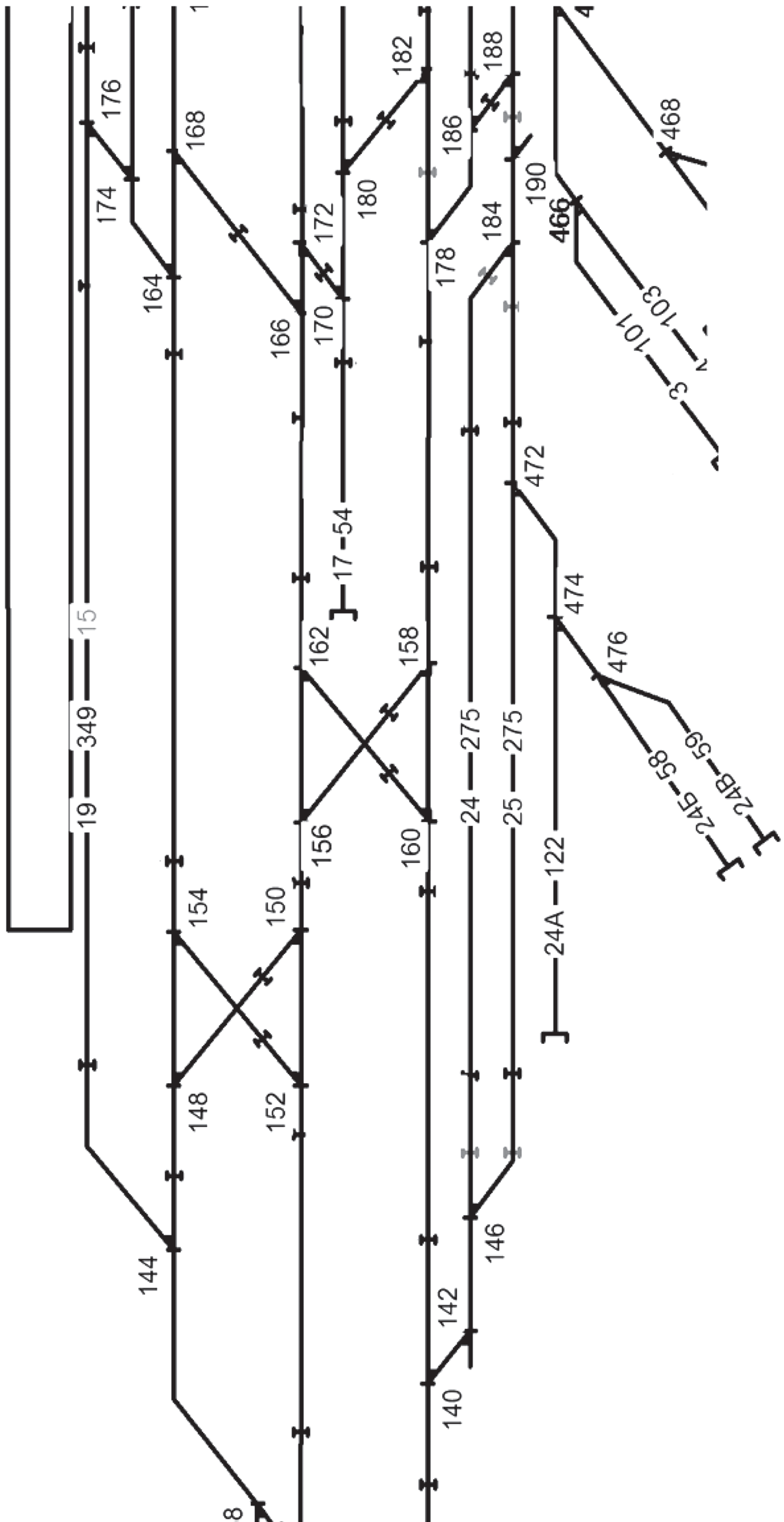

Figure 2. Layout of the station for which the collision probability is calculated

For switches nos. 144, 236, 149-161, 151-147 we have $\lambda_{Sh}=\tilde{\lambda}_{Sh}/4\approx 0{,}168$, $\lambda_{PU}=\tilde{\lambda}_{PU}/4\approx 0{,}0006$, $\lambda_{CU}=\tilde{\lambda}_{CU}/4\approx$ $\approx 0{,}009$.

Let us number the switches according to the order in which they are crossed by the train (see item 9 of the algorithm): 115→1, 121→2, 151-147→3, 149-161→4, 244→5, 238→6, 236→7, 176→8, 144→9, 138→10.

The probability of collision on non-insulated switches nos. 144, 236, 149-161, 151-147 is calculated using the formulas (see item 11 of the algorithm)

$$P_{Sh}(A_{2:3})=\lambda_{Sh}\left(\frac{l_P}{v_P}+\frac{l_{Sh}}{v_{Sh}}\right)(P_{Sh}(1+P_P)+P_P)+$$
$$+\lambda_{CU}\left(\frac{l_P}{v_P}+\frac{l_{Sh}}{v_{Sh}}\right)(P_{CU}(1+P_P)+P_P)+$$
$$+\lambda_{PU}\left(\frac{l_P}{v_P}+\frac{l_{PU}}{v_{PU}}+\tau_{PU}\right)P_{PU}(1+P_P)+\lambda_S P_P\tau_S+$$
$$+(\lambda_{Sh}P_{Sh}+\lambda_{PU}P_{PU}+\lambda_{CU}P_{CU})P_{PS}\tau_{PS}=0{,}168\cdot$$
$$\cdot\left(\frac{0{,}48}{42}+\frac{0{,}2}{4{,}2}\right)\cdot(10^{-8}\cdot(1+10^{-7})+10^{-7})+0{,}009\cdot$$
$$\cdot\left(\frac{0{,}48}{42}+\frac{0{,}2}{4{,}2}\right)\cdot(1{,}25\cdot10^{-4}\cdot(1+10^{-7})+10^{-7})+0{,}0006\cdot$$
$$\cdot\left(\frac{0{,}48}{42}+\frac{0{,}02}{2}+0{,}01\right)\cdot 5{,}5\cdot10^{-6}\cdot(1+10^{-7})=6{,}8\cdot10^{-8}.$$

$$P_{Sh}(A_{2:4})=P_{Sh}(A_{2:7})=P_{Sh}(A_{2:9})=0{,}168\cdot\left(\frac{0{,}48}{42}+\frac{0{,}2}{4{,}2}\right)\cdot$$
$$\cdot(10^{-8}\cdot(1+10^{-7})+10^{-7})+0{,}009\cdot\left(\frac{0{,}48}{42}+\frac{0{,}2}{4{,}2}\right)\cdot$$
$$\cdot(1{,}25\cdot10^{-4}\cdot(1+10^{-7})+10^{-7})+0{,}0006\cdot\left(\frac{0{,}48}{42}+\frac{0{,}02}{2}+0{,}01\right)\cdot$$
$$\cdot 5{,}5\cdot10^{-6}\cdot(1+10^{-7})=6{,}8\cdot10^{-8}.$$

For the insulated switches nos. 138, 176, 238, 244, 121, 115 the probability of collision equals to zero, i.e.

$$P_{Sh}(A_{2:1})=P_{Sh}(A_{2:2})=P_{Sh}(A_{2:5})=$$
$$=P_{Sh}(A_{2:6})=P_{Sh}(A_{2:8})=P_{Sh}(A_{2:10})=0.$$

The probability of at least one collision involving passenger train no. 255N equals to (see item 14 of the algorithm)

$$P_{Sh}(A_1\mid R_2)=1-1\cdot1\cdot(1-6{,}8\cdot10^{-8})\cdot(1-6{,}8\cdot10^{-8})\cdot$$
$$\cdot1\cdot1\cdot(1-6{,}8\cdot10^{-8})\cdot1\cdot(1-6{,}8\cdot10^{-8})\cdot1=2{,}7\cdot10^{-7}.$$

The probability of the use of routes R_3, R_4, R_5, R_6 equals to (see item 8 if the algorithm) as

$$P(R_3)=P(R_4)=P(R_5)=P(R_6)=\frac{0}{2+1+0+0+0+0}=0.$$

Therefore the probabilities $P_{Sh}(A_1\mid R_3)$, $P_{Sh}(A_1\mid R_4)$, $P_{Sh}(A_1\mid R_5)$, $P_{Sh}(A_1\mid R_6)$ of at least one collision on those routes do non need to be calculated.

The probability of at least one collision involving passenger train no. 255N while crossing the station equals to (see item 17 of the algorithm)

$$P_{Sh}(A_1)=\sum_{k=1}^{K}P_{Sh}(A_1\mid R_k)P(R_k)=\sum_{k=1}^{6}P_{Sh}(A_1\mid R_k)P(R_k)=$$
$$=2{,}7\cdot10^{-7}\cdot\frac{2}{3}+2{,}7\cdot10^{-7}\cdot\frac{1}{3}=2{,}7\cdot10^{-7}.$$

Now, let us calculate the probability of at least one collision for a station equipped with MALS during a year.

Let the previous transits across the station for all trains be unknown. Then, the probability of at least one collision between passenger trains that pass the station without stopping and a shunting consist in May equals to

$$P_{Sh}(A_{\text{May}})=0{,}00002.$$

The probability of at least one collision between passenger trains that pass the station without stopping and a shunting consist in August equals to

$$P_{Sh}(A_{\text{August}})=0{,}00008.$$

The traffic density in August is peak, i.e. in other months the probability of at least one collision will be lower. This assumption is confirmed by the timetable analysis. From here it follows that the probability of at least one collision during a year is evaluated with the value

$$P_{Sh}(A_{\text{year}})=1-(1-0{,}00008)^{12}=0{,}00096.$$

If the MALS system is used in the station, the probability of at least one collision involving a passenger train moving through the station is most affected by the summand related to the coupling. That is due to the fact that the probability of signal violation by a shunting consist after coupling with the "coupling" mode off turns out to be higher than in the "pull up" mode or while performing the other shunting operations. If a freight train is considered, the probability of its collision with a shunting consist is most affected by the summand not associated with the coupling or pulling up. That is due to the high probability of signal violation by the freight train driver. The probability of at least one collision involving a passenger train is as expected lower than the probability of at least one collision involving a freight train. That is also due to the fact that the probability of signal violation by a freight train driver is two orders of magnitude higher than the probability of signal violation by a shunting consist driver, as well as the fact that freight trains are longer than passenger trains, therefore they occupy a switch longer and the probability of collision will last longer as well.

If we compare the resultant probability of at least one collision during a year with the respective probability in [2] for shunting engines not equipped with MALS, this probability will turn out to be an order of magnitude lower.

6. Conclusion

The paper has examined the matters related to the evaluation of the risk of collision in railway stations in which shunting engines may be equipped with the MALS system. The main focus is on the method of calculation of the probability of collision between passenger trains and shunting consists in a railway station based on the shunting consist traffic density and specific passenger train schedule. The use of MALS in a railway station helps significantly reduce the probability of collision within a year.

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