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Selected Issues of Safe Operation of the Railway Traffic Control System in the Event of Exposition to Damage Caused by Lightning Discharges

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Abstract: Lightning discharge becomes a serious source of interference and damage for electronic and electrical power systems. Safe and reliable operation of railway traffic control systems requires proper protection against the effects of lightning. However, the current standards on lightning protection, PN-EN/EN/IEC 62305, do not cover railway objects. Moreover, there are no other standards or recommendations dedicated to the railway. The paper is an attempt to apply the procedure of lightning risk management according to PN-EN 62305-2 to select the proper protection measures in railway objects. A case study for the signal box with installed relaying and digital stations of the railway traffic control system is analyzed. The analysis comprises calculations based on the current standard PN-EN 62305-2:2012 but including the issues specific to railway traffic control. The risks of lightning losses have been calculated for two cases: without lightning protection measures and with protection measures proposed to decrease the risks below the tolerable values. The results show that a practically effective solution to reduce the risks is applying surge protective devices with proper characteristics. Another way is replacing unshielded incoming lines with shielded ones of given shield bonding way, and supplementing it with surge protective devices when necessary.

Keywords: lightning protection; lightning impact on railway traffic control devices; lightning protection level; lightning risk management; risk of lightning loss in railway systems



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1. Introduction

Observations from satellite recordings show that there are on average about 2000 thunderstorms on earth at any given moment [1–5]. As a result of their impact, various damages to both private and public facilities are observed. Railway installations are also significantly exposed to such influences. In the case of serious damage to equipment, PKP commissioning analyzes the strokes recorded by lightning location systems. For example, the recorded strokes were analyzed using the LINET system [1]. The system showed a lot of strokes at a distance of 2 km from the affected railway line [1,6–9]. The place of the discharge is located by the system with an error of 150–200 m. The location method is based on the use of the TOA (Time-of-Arrival) technique optimized through the use of GPS. The mean time resolution error for the system is 0.2 μ s [9,10]. On the analyzed section of the line, at a distance of 20 m from the track axis and 40 m from the non-traction line (NTL), lightning currents with the highest value of 157.5 kA were recorded [1].

These data should be taken into account in particular by designers through a thorough analysis of storm maps when designing railway traffic control systems and choosing its devices. Moreover, knowledge about lightning occurrence is a key point in adopting adequate protection measures against direct and indirect effects of lightning discharges [10–14]. However, the random occurrence and a large number of factors influencing the hazard,

its consequential damage, and related loss make the decision about the necessity and the method of lightning and surge protection complicated [15–17]. Therefore the decision should be preceded with an estimation of the risk of losses, which facilitates the evaluation of the resulting hazards caused by lightning and the related damage.

Lightning discharge is one of the most important factors that influence the safety of railway traffic control (RTC) systems [18]. This is related to a high exposition of the RTC system to atmospheric discharges (wire communication over long distances) and low immunity levels of the system components. Moreover, the consequences of damage to the system may be very serious.

Safe and reliable operation of RTC systems requires adopting proper protection measures against direct and indirect effects of lightning. According to Polish standard on lightning protection PN-EN 62305 [19–23], which is identical to the corresponding European and International standards EN/IEC 62305 [19–23], and similar to ITU Recommendation K.39 [24], the choice of protection measures must be based on the analysis of the risk of lightning losses [25,26], which is described in part 2 of the standards 62305-2 [20,21]. This permits the correct and economic selection of lightning protection systems and other protection measures, for the given object type, its equipment, and the way of using them [16]. The standards are applicable for many types of building structures. They can be easily adapted for analysis of typical private and public buildings, e.g., residential, schools, museums, telecommunication centers, commercial and industrial facilities [15,16,18]. However, the standards do not cover railway objects [19–23]. These objects have their own specific features which are not addressed in the standards 62305-2 [20,21] or whose application in the standard procedure is not straightforward. Moreover, there is no dedicated standard or other recommendations that could be used for railway objects in this respect. It is, therefore, necessary to develop special recommendations for internal use within the railway.

The paper is an attempt to apply the procedure of lightning risk management, according to PN-EN 62305-2:2012 [21], to select the proper protection measures in railway objects. The analysis of the risk of losses due to atmospheric discharges in the railway traffic control system has been presented. A case study for the chosen object type—signal box with installed relaying and digital station of the railway traffic control system and a fragment of a track section—has been analyzed. In the analysis, a track foreman fragment with three-level crossings, a feeding line, an antenna mast, two telephone lines, three-level crossings, and two farthest advanced signals are taken into account. The analysis has been done with calculation performed according to PN-EN 62305-2:2012 [21]. As part of the lightning risk management procedure, the risks of lightning losses without and with protection measures have been calculated. This has shown a general necessity of application of specific overvoltage protection measures for the considered type of railway objects.

2. Materials and Methods

2.1. Lightning Risk Management According to PN-EN 62305-2:2012

According to the standard PN-EN 62305-2:2012 pt. 3.1.31 [21] the lightning risk R is defined as the probable average value of one year's loss (people and goods) as a consequence of lightning, related to the entire value (people and goods) of the object subjected to the protection. There are four types of risk R (R_1 , R_2 , R_3 , R_4) of corresponding losses L (L_1 , L_2 , L_3 , L_4), dependent on the object type:

- R_1 : Risk of loss of life or permanent injury L_1 ;
- R_2 : Risk of loss of service to the public L_2 ;
- R_3 : Risk of loss of cultural heritage L_3 ;
- R_4 : Risk of loss of economic value L_4 .

Each type of risk R is the sum of its components R_X related to the source S and the type D of damage causing the loss (Table 1). The risk components R_X are calculated based on the overall formula:

$$R_X = N_X \times P_X \times L_X, \quad (1)$$

where:

N_X —Number of dangerous events related to particular source and type of damage (Table 1);

P_X —Probability of damage caused by one dangerous event of a particular source of damage;

L_X —Loss factor that allows estimating the loss related to the damage.

Table 1. Components R_X of the risk R , related to the source S and type D of damage [20,21].

Source of Damage Type of Damage	Lightning Flash:				Risk Related to the Type of Damage D
	To the Structure (S1)	Near the Structure (S2)	To a Connected Line (S3)	Near a Connected Line (S4)	
Injuries due to Electric Shock (D1)	$R_A = N_D \times P_A \times L_A$	NA ¹	$R_U = (N_L + N_{DJ}) \times P_U \times L_U$	NA ¹	$R_A + R_U$
Physical Damage (D2)	$R_B = N_D \times P_B \times L_B$	NA ¹	$R_V = (N_L + N_{DJ}) \times P_V \times L_V$	NA ¹	$R_B + R_V$
Failure of Internal Systems (D3)	$R_C = N_D \times P_C \times L_C$	$R_M = N_M \times P_M \times L_M$	$R_W = (N_L + N_{DJ}) \times P_W \times L_W$	$R_Z = N_I \times P_Z \times L_Z$	$R_C + R_M + R_W + R_Z$
Risk Related to the Source of Damage S	$R_A + R_B + R_C$	R_M	$R_U + R_V + R_W$	R_Z	$R = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z$

¹ NA—not applicable, i.e., no type of damage for a particular source of damage. N_D —number of dangerous events due to lightning flashes to the object in concern. N_M —number of dangerous events due to lightning flashes to the ground near the object. N_L —number of dangerous events due to lightning flashes to the line incoming to the object. N_{DJ} —number of dangerous events due to lightning flashes to the adjacent structure, i.e., the object at the opposite end of the line incoming to the object in concern. N_I —number of dangerous events due to lightning flashes to the ground near the incoming line.

In the formulas, the number of dangerous events depends on the lightning occurrence as well as the geometry, main properties, and localization of the object and external lines connected to it. The probability of damage is dependent on the characteristics of the object and incoming external lines as well as the protection measures adopted for the object and lines. The loss factor is dependent on the type and purpose of the object as well as the characteristics of the object and connected lines. The detailed rules for calculating or determining particular factors N_X , P_X , and L_X are quite complex [21].

Qualifying the necessity of the lightning protection for the object according to the standard, the designer should take into account all the types of risks R that are applicable for the object, depending on its type and purpose. Then, for each type of risk identified in the object, he should follow the management risk procedure:

1. Identify the components R_X forming the risk R ;
2. Calculate the components R_X and the entire risk R ;
3. Identify the value of the tolerated risk R_T , based on recommendations of applicable standards or bodies having jurisdiction;
4. Compare the calculated risk R with the tolerated value R_T .

In the case of $R \leq R_T$, lightning protection is not necessary. For $R > R_T$, it is necessary to choose protection measures that have an impact on the probabilities of damage P_X and the loss factors L_X , to reduce the risk R to or below the tolerated value R_T .

As a result of such analysis, one can decide on the use of protection measures permitting the minimization of losses in the object and the proper selection of the lightning protection level. Furthermore, if the object is divided into zones, the procedure permits the correct and economic selection of protection measures individually for particular zones [20,21,27].

2.2. Application of PN-EN 62305-2:2012 Lightning Risk Procedure to the Case Study—The Railway Object

The railway object chosen for the case study analysis is a signal box containing relaying and computer devices of the railway traffic control (RTC) system. The object is presented in Figure 1 [1,28,29]. The equipment inside the object is connected to the following external lines:

- electrical power feeding line 230/400 V connected to the low voltage power system;
- two telecommunication lines;
- antenna cable connected to the antenna installed on a mast at the roof;
- two feeding lines 230/500 V of automatic line block system;
- three control lines of automatic level crossings;
- two signal lines for remote signaling;
- signal line connected to station equipment.

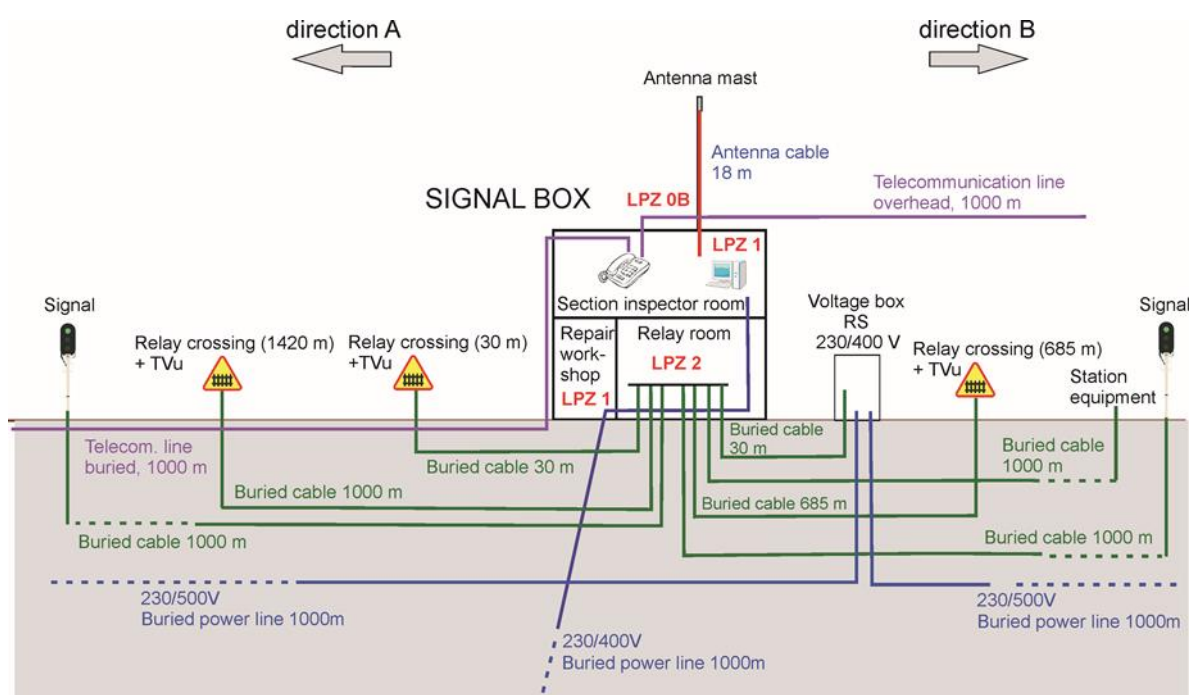


Figure 1. Analyzed railway objects with incoming external lines and devices [1,28,29].

For each line the following characteristics were determined: the type (overhead/underground) and length of the line (outside the object), the environment (urban/suburban/rural), an adjacent structure connected to the line, the type of wiring (shielded/unshielded) and the lowest impulse withstand voltage of internal systems connected to the line.

For determining the number of dangerous events N_X in the calculation of the risk according to (1) an essential parameter is the density of lightning discharges to earth N_g . It determines the number of lightning discharges to the ground per square kilometer per year. For areas, where the object is located, according to the density maps of lightning discharges, N_g is approx. 2.7 per km^2 per year [21].

The number of dangerous events N_X is dependent also on the equivalent collection area of lightning flashes, which is calculated based on geometrical dimensions of the object or the incoming external line in concern. The equivalent collection area is calculated under the assumption that the object or line is located on flat ground and there are no other structures in the vicinity. Then, specific conditions of the object and incoming lines are taken into account by using defined factors dependent on the location (surrounding structures and landform), environment (rural, suburban, urban, etc.), line installation (aerial or buried), and line-type (with or without a transformer at the entry to the object) [19,21].

The characteristics of the object and incoming lines used to determine the number of dangerous events are presented in Appendix A (Tables A1–A11).

The equivalent collection areas of lightning flashes to and near the incoming lines given in Tables A2–A11 cannot be used in calculations of the numbers of dangerous events because of overlapping of the areas related to lines following the same or similar routes [19,21]. This is the first difficulty to come across in the considered railway object, which results from a large number of incoming external lines. To take this into account, each incoming line was classified to one of the four approximate routes A, B, C, or D, according to the direction it follows. Then, the equivalent collection area for a given route (A, B, C, D) was determined, as being the worst case among the particular collection areas of the lines following the route (the largest collection area calculated). The results are shown in Table 2.

Table 2. Worst case parameters and collection areas related to the incoming lines that follow the same routes.

Route	Line Length L_L (m)	Product of Line Factors $C_I \times C_T \times C_E$ (-)	Equivalent Collection Area of Direct Flashes A_L (m ²)	Equivalent Collection Area of Near Flashes A_I (m ²)	Product of Adjacent Structure Factors $C_{DJ} \times C_T$ (-)	Collection Area of Flashes to the Adjacent Structure A_{DJ} (m ²)
A ¹	1,420	0.5	56,400	4,260,000	1	0
B ²	1,030	0.5	40,800	3,090,000	1	0
C ³	1,000	0.25	39,600	2,775,000	1	0
D ⁴	1,000	0.5	39,600	2,775,000	1	0

¹ Lines of route A: feeding 230/500 V direction A; control to level crossings 1 and 2; signal for remote signaling 1. ² Lines of route B: feeding 230/500 V to voltage box, direction A and direction B; Control to level crossing 3; signal to station equipment; signal for remote signaling 2.

³ Lines of route C: feeding 230/400 V; telephone 1. ⁴ Lines of route D: telephone 2.

According to PN-EN 62305-2:2012 [21], for efficient and economic selection of protection measures that influence the probabilities of damage P_X and to take into account different characteristics of particular parts of the object that influence the loss factors L_X (Table 1), the object was divided into zones. The zones created for the purpose of risk analysis according to PN-EN 62305-2:2012 [21] have been coordinated with the lightning protection zone (LPZ) concept according to PN-EN 62305 [19,21–23]. This assumption was taken for the case if, following the risk management procedure, it turned out necessary to apply protection measures.

The zoning can be made taking into account such criteria as the type of ground and floors, fire-proof barriers, spatial shielding, arrangement of internal systems, existing or proposed protection measures, type of losses, and amount of losses. Considering the lightning protection zones (LPZ), i.e. the zones for which the lightning electromagnetic environment is defined according to the LPZ concept, the following zones Z have been defined for the object—signal box—(Figure 1):

- For LPZ 0A or 0B (outside the signal box):
 - Z1—around the signal box, access from the ground;
 - Z2—around the antenna mast, access from the roof of the signal box;
- For LPZ 1 (inside the signal box):
 - Z3—section inspector duty room;
 - Z4—repair workshop room;
- For LPZ 2 (inside the signal box with better shielding properties than LPZ 1 if needed):
 - Z5—relay room.

The lightning protection zones LPZ are defined in standard PN-EN 62305 as follows:
LPZ 0A: Zone unprotected against lightning electromagnetic pulse.

LPZ 0B: Zone protected against direct lightning strikes by external lightning protection system (LPS). Equipment is exposed to parts of lightning currents and full lightning electromagnetic fields.

LPZ 1: Internal zone, where the failure surge currents and voltages are limited by equipotential bonding and surge protective devices (SPD), and the lightning electromagnetic field is attenuated by spatial shielding at the zone boundary.

LPZ 2 . . . n: Internal zones, where current and voltage impulses are further limited by equipotential bonding and additional SPD, and the lightning electromagnetic field is further limited by additional spatial shielding at the zones' boundaries.

Determining the values of probabilities of damage P_X (Table 1), it is necessary to know specific characteristics of the object, incoming external lines, internal electrical and electronic systems installed in the object, and applied protection measures against electric shock, lightning, and overvoltage. These characteristics can be summarized as follows:

1. External lightning protection system (LPS) on the object—no external LPS present;
2. Protection against electric shock due to direct lightning flash to the object—no protection;
3. Screening effectiveness of the structure at the boundary LPZ 0/1—no shielding;
4. Screening effectiveness of internal shields, i.e., within LPZ 1—no internal shielding;
5. Type, shielding, grounding, and isolation conditions of the incoming lines:
 - antenna cable line—telecommunication (TLC), aerial, shielded with shield resistance higher than $5 \Omega/\text{km}$ up to $20 \Omega/\text{km}$, no connection at the entrance (internal system);
 - electrical power feeding line 230/400 V—power, buried, unshielded;
 - electrical power feeding lines 230/500 V—power, buried unshielded;
 - telecommunication line 1—TLC, buried, unshielded;
 - telecommunication line 2—TLC, aerial, unshielded;
 - control lines of automatic level crossings (1, 2, and 3)—TLC/data, buried, unshielded;
 - signal line for station equipment—TLC/data, buried, unshielded;
 - signal lines for remote signaling (1 and 2)—TLC/data, buried, unshielded;
6. Type of internal wiring of the internal electrical and electronic systems:
 - antenna system—shielded;
 - electrical power 230/400 V—unshielded, routing precautions to avoid large loops;
 - electrical power 230/500 V—unshielded, routing precautions to avoid large loops;
 - telecommunication (1 and 2)—unshielded, routing precautions to avoid large loops;
 - control of level crossings (1, 2, 3)—unshielded, routing precautions to avoid large loops;
 - station equipment—unshielded, routing precautions to avoid large loops;
 - remote signaling (1, 2)—unshielded, routing precautions to avoid large loops;
7. Lowest impulse withstand voltage—from 1.0 kV to 2.5 kV, depending on the zone and the internal system;
8. Protection against electric shock due to direct lightning flash to the incoming lines—electrical insulation and/or physical restrictions, depending on the zone and the incoming line;
9. Coordinated surge protective devices (SPDs) in the internal electrical and electronic systems, according to PN-EN 62305-4 [23]—no coordinated SPDs in all systems and zones;
10. Equipotential bonding provided by SPDs at the entry of the incoming lines to the object, according to PN-EN 62305-3 [22]—no SPDs in all systems and zones.

Some of these characteristics extend to the entire object or system and some are specific only for certain zones Z. The detailed information about these characteristics is presented in Appendix B.

The specific characteristics of the considered object and its contents, which influence the loss factors L_X (Table 1), are presented in Tables 3–7.

Table 3. Factors decreasing and increasing the number of losses in the object.

Decreasing or Increasing Factor	Symbol	Characteristics				
		Z1	Z2	Z3	Z4	Z5
Type of surface of soil or floor	r_t	Concrete, agriculture	Asphalt	Linoleum	Linoleum	Linoleum
Provisions taken to reduce the consequences of fire	r_p	Hydrant	Fire extinguisher	Fire extinguisher	Fire extinguisher	Fire extinguisher
Risk of fire or explosion of the structure	r_f	Ordinary	Ordinary	Ordinary	Ordinary	Ordinary
Special hazard related to panic and evacuation	h_z	No special hazard	No special hazard	Low level of panic	Low level of panic	Low level of panic

Table 4. Characteristics influencing the typical mean values of losses depending on the type of object.

Type of Loss	Symbol	L _T	L _F	L _O	L _{OE} ¹
		Injuries	Physical Damage	Failure of Internal System	Environmental Effects of Failure ¹
Loss of human life	L ₁	All types	Other	No danger for people inside	Specific: 1.0×10^{-41}
Loss of service to the public ¹	L ₂	-	Specific: 1.0×10^{-21}	Specific: 1.0×10^{-31}	
Loss of cultural heritage	L ₃	-	No cultural heritage	-	
Economic loss ¹	L ₄	No animals present	Specific: 2.0×10^{-11}	Specific: 2.0×10^{-31}	

¹ Not included in the standard PN-EN/EN 62305-2 for railway objects; Proposed for the considered case.**Table 5.** Presence of persons during the year in the structure, relevant to the loss of human life (L₁).

Conditions	Symbol	Value				
		Z1	Z2	Z3	Z4	Z5
Number of persons in the zone	n_z	0	0	2	2	1
Total number of persons in the structure	n_t	5				
Time in hours per year for which people are present in the zone	t_z	0	0	8760	2090	2090
Time of presence of people in the dangerous places outside the object ¹	t_e	2920 ¹				

¹ Not included in the standard PN-EN/EN 62305-2 for railway objects; Proposed for the considered case.**Table 6.** Number of users served by the object, relevant to the loss of service to the public (L₂).

Conditions	Symbol	Value				
		Z1	Z2	Z3	Z4	Z5
Number of users served by the zone (average per day) ¹	n_z	0 ¹	0 ¹	5000 ¹	0 ¹	20,000 ¹
Total number of users served by the object (average per day) ¹	n_t	25,000 ¹				

¹ Not included in the standard PN-EN/EN 62305-2 for railway objects; Proposed for the considered case.

Table 7. Economic value of the object and its contents, relevant to the economic loss (L_4).

Conditions	Symbol	Value (Euro)				
		Z1	Z2	Z3	Z4	Z5
Value of animals in the zone	c_a	0	0	0	0	0
Value of building relevant to the zone	c_b	0	0	150,000	150,000	75,000
Value of content in the zone	c_c	0	5000	20,000	15,000	10,000
Value of internal systems, including their activities, in the zone	c_s	0	10,000	30,000	10,000	25,000
Total value of the object	c_t	500,000				

The risk of fire or explosion of the structure (Table 3) determines an important factor in the evaluation of lightning losses. The gradation of the fire risk is based on values of specific fire load and it is defined in the standard [21]. The fire load is fixed by an expert of fire precautions or defined after consultation with the owner of the building or with his insurance—firm. The fire risk for the analyzed object has been qualified as usual (ordinary or common).

Considering the number of persons present within the zones (Table 5), a lack of special hazard was assumed within zones Z1 and Z2, and a low level of panic for zones Z3, Z4, and Z5 (Table 3).

For calculation of the risks of lightning losses using formulas from Table 1, the descriptive characteristics presented in Tables 3 and A1–A15, Tables 4–7, were replaced by corresponding values of the factors and parameters, according to the rules and formulas given in PN-EN 62305-2:2012 [21] with keeping the original symbols (included in the tables).

As the standard does not cover the railway objects, in the calculation procedure it was necessary to propose the following specific data and/or solutions:

- Calculating the equivalent collection areas of lightning flashes to and near the external lines (power, telecom, data) incoming to the object following the same or similar routes when collection areas of particular lines overlap (Table 2), and selecting the worst case characteristics (Tables A13–A15) for estimating the probabilities of damage;
- Proposing the typical mean values of losses of service to the public and of economic value due to physical damage L_F and failures of internal electrical and electronic systems L_O , which can be regarded specific for the objects (Table 4);
- Proposing the typical mean value of loss of human life due to failures of internal electrical and electronic systems for people present in the dangerous place outside the object (zone ZE) L_{OE} (Table 4) and the time of presence of people in the place t_e (Table 5), and calculating the corresponding risk of loss of human life in the outside zone ZE;
- Proposing the numbers of users served by the object, relevant to the loss of service to the public, as specific to the considered objects (Table 6);
- Proposing the economic value of the object and its content, relevant to the economic loss, as specific to the considered objects (Table 7).

In the case of railway objects, the failure of internal systems due to lightning may involve loss of human life or permanent injury of people away from the object. For example, in the case of railway and road collision due to false operation of the RTC system. This effect is not taken into account in the standards (62305-2). However, it was included in the analysis in a similar way as the case when the physical damage involves the environment and surrounding structures (including people) [21].

For this purpose, additional losses (L_{CE} , L_{ME} , L_{WE} , and L_{ZE}) were taken into account as the parts of the total losses (L_{CT} , L_{MT} , L_{WT} , and L_{ZT}) according to formulas (2)–(6):

$$L_{CT} = L_C + L_{CE} \quad (2)$$

$$L_{MT} = L_M + L_{ME} \quad (3)$$

$$L_{WT} = L_W + L_{WE} \quad (4)$$

$$L_{ZT} = L_Z + L_{ZE}, \quad (5)$$

$$L_{CE} = L_{ME} = L_{WE} = L_{ZE} = L_{OE} \times t_e / 8760, \quad (6)$$

where:

L_{OE} —the percentage of people injured outside the object due to failure of internal systems (Table 4);

t_e —time of presence of people in the dangerous place outside the object (Table 5);

8760—number of hours within a year.

The components of the risk of losses related to the presence of people in the dangerous place outside the object (zone ZE) was calculated according to the general formula (1), where the loss L_{XE} (L_{CE} , L_{ME} , L_{WE} , L_{ZE}) was estimated according to (6) and the corresponding probability of damage P_{XE} (P_{CE} , P_{ME} , P_{WE} , P_{ZE}) was determined as the worst case from the particular values of probability P_X (P_C , P_M , P_W , P_Z), assigned to the zones of the object (Z1–Z5).

Similarly, the failure of internal systems due to lightning may involve loss of economic value away from the object. This effect, however, was not taken into account in the analysis due to difficulties in determining the typical loss of economic value outside the object.

The data presented in this section were taken as input for calculation of the risks of lightning losses in the object, in the case where no protection measures against lightning electromagnetic pulse are installed. This was taken as the base case. Then, the calculation of the risks was performed again for the case for which a set of lightning protection measures was proposed to decrease the risks to or below the tolerated values. The calculations were performed using MS Excel calculation sheets, developed specifically for the considered railway objects according to the full procedure recommended in PN-EN 62305-2:2012 [21].

3. Results

There are three types of losses relevant to the object: loss of human life (L_1), loss of service to the public (L_2), and loss of economic value (L_4). The loss of cultural heritage (L_3) is not applicable. Hence, the corresponding risks R_1 , R_2 , and R_4 were considered. For the decision on the necessity of protection measures the tolerated values of the risks R_{T1} , R_{T2} and R_{T4} were adopted as shown in Table 8.

Table 8. Tolerated values of lightning loss risks adopted for the analysis.

Type of Loss	Tolerable Risk		
	Symbol	Value	Reference
Loss of human life	R_{T1}	1.0×10^{-5}	PN-EN 62305-2:2012 [21]
Loss of service to the public	R_{T2}	1.0×10^{-3}	PN-EN 62305-2:2012 [21]
Loss of economic value	R_{T4}	1.0×10^{-4}	Proposed

3.1. Object without Protection Measures—Base Case

Calculating the risk of lightning losses and its components requires first evaluating the numbers of dangerous events N_X , probabilities of damage P_X , and losses L_X (Table 1). The standard procedures for evaluating these factors are complex [21] and are not included in the paper. The factors are partly calculated using numerical data and partly determined based on descriptive characteristics. For the considered base case object (without protection measures), the input data are shown in Tables 2 and A1–A11, Tables A12–A15 and Tables 3–7. The calculated/estimated numbers of dangerous events, probabilities of damage, and losses are shown in Tables 9–11, respectively.

Table 9. Calculated numbers of dangerous events for the base case object.

Lightning Flashes Related to:	Number of Dangerous Events Due to Flashes:	Symbol	Value
the object in concern	to the object	N_D	1.95×10^{-2}
	near the object	N_M	$2.19 \times 10^{+0}$
lines incoming from direction A	to the line	$N_{L(A)}$	7.61×10^{-2}
	near the line	$N_{I(A)}$	$5.75 \times 10^{+0}$
	to an adjacent structure connected to the line	$N_{DJ(A)}$	$0.00 \times 10^{+0}$
lines incoming from direction B	to the line	$N_{L(B)}$	5.51×10^{-2}
	near the line	$N_{I(B)}$	$4.17 \times 10^{+0}$
	to an adjacent structure connected to the line	$N_{DJ(B)}$	$0.00 \times 10^{+0}$
lines incoming from direction C	to the line	$N_{L(C)}$	2.67×10^{-2}
	near the line	$N_{I(C)}$	$1.87 \times 10^{+0}$
	to an adjacent structure connected to the line	$N_{DJ(C)}$	$0.00 \times 10^{+0}$
lines incoming from direction D	to the line	$N_{L(D)}$	5.35×10^{-2}
	near the line	$N_{I(D)}$	$3.75 \times 10^{+0}$
	to an adjacent structure connected to the line	$N_{DJ(D)}$	$0.00 \times 10^{+0}$

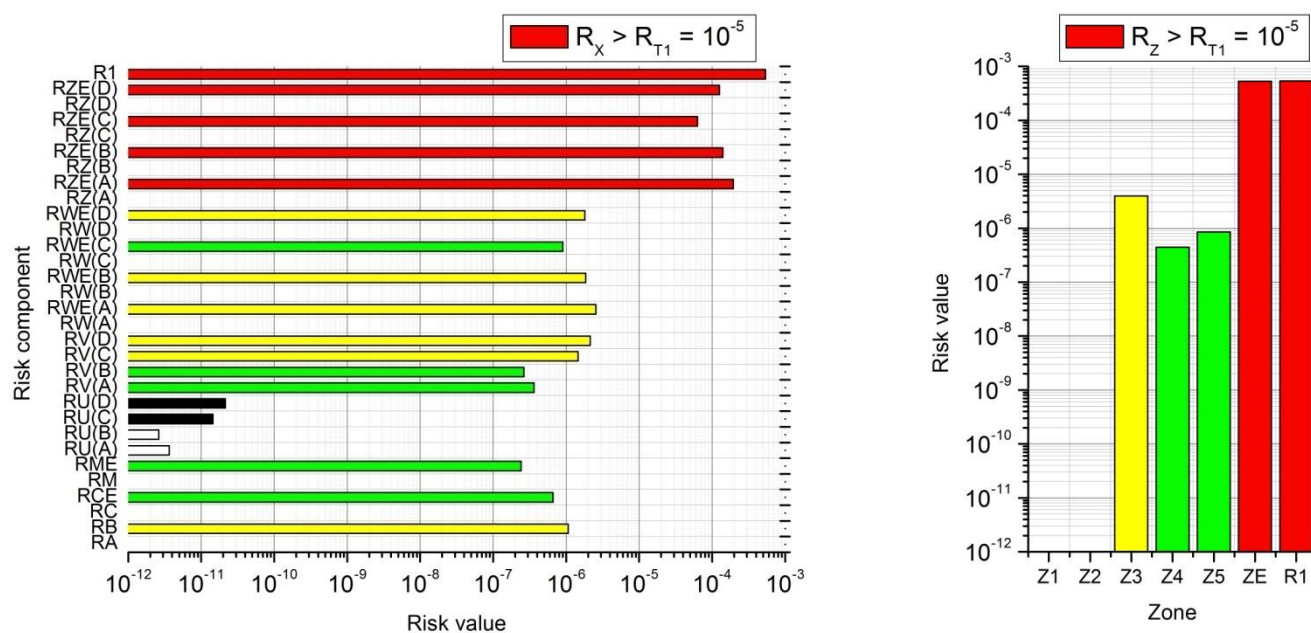
Table 10. Estimated probabilities of damage for the base case object.

Lightning Flashes:	Type of Damage	Symbol	Probability of Damage				
			Z1	Z2	Z3	Z4	Z5
To the object in concern	Injuries	P_A	1	1	1	1	1
	Physical damage	P_B	1	1	1	1	1
	Failure of internal systems	P_C	1	0	1	1	1
Near the object	Failure of internal systems	P_M	3.7×10^{-1}	1.0×10^{-8}	8.4×10^{-2}	6.4×10^{-3}	3.2×10^{-1}
To the lines incoming from direction A	Injuries	$P_{U(A)}$	0	0	0	0	1.0×10^{-2}
	Physical damage	$P_{V(A)}$	1	0	0	0	1
	Failure of internal systems	$P_{W(A)}$	1	0	0	0	1
Near the lines from direction A	Failure of internal systems	$P_{Z(A)}$	1	0	0	0	1
To the lines incoming from direction B	Injuries	$P_{U(B)}$	0	0	0	0	1.0×10^{-2}
	Physical damage	$P_{V(B)}$	1	0	0	0	1
	Failure of internal systems	$P_{W(B)}$	1	0	0	0	1
Near the lines from direction B	Failure of internal systems	$P_{Z(B)}$	1	0	0	0	1
To the lines incoming from direction C	Injuries	$P_{U(C)}$	0	0	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}
	Physical damage	$P_{V(C)}$	1	0	1	1	1
	Failure of internal systems	$P_{W(C)}$	1	0	1	1	1
Near the lines from direction C	Failure of internal systems	$P_{Z(C)}$	1	0	1	0.3	0.6
To the lines incoming from direction D	Injuries	$P_{U(D)}$	0	0	1.0×10^{-2}	0	0
	Physical damage	$P_{V(D)}$	1	0	1	0	0
	Failure of internal systems	$P_{W(D)}$	1	0	1	0	0
Near the lines from direction D	Failure of internal systems	$P_{Z(D)}$	1	0	1	0	0

Table 11. Calculated losses for the base case object.

Type of Loss	Type of Damage	Symbol	Loss				
			Z1	Z2	Z3	Z4	Z5
Human life of injury	Injuries	L_A	0	0	-	-	-
	Injuries	L_U	-	-	4.0×10^{-8}	9.5×10^{-9}	4.8×10^{-9}
	Physical damage	$L_B = L_V$	0	0	4.0×10^{-5}	9.5×10^{-6}	4.8×10^{-6}
	Failure of internal systems	$L_C = L_M = L_W = L_Z$	0	0	4.0×10^{-4}	9.5×10^{-5}	4.8×10^{-5}
	Environmental effects of failure of internal systems	$L_{CE} = L_{ME} = L_{WE} = L_{ZE}$			3.4×10^{-5}		
Service to the public	Physical damage	$L_B = L_V$	0	0	1.0×10^{-5}	0	4.0×10^{-5}
	Failure of internal systems	$L_C = L_M = L_W = L_Z$	0	0	2.0×10^{-4}	0	8.0×10^{-4}
Economic value	Injuries	L_A	0	0	-	-	-
	Injuries	L_U	-	-	0	0	0
	Physical damage	$L_B = L_V$	0	3.0×10^{-5}	4.0×10^{-4}	3.5×10^{-4}	2.2×10^{-4}
	Failure of internal systems	$L_C = L_M = L_W = L_Z$	0	4.0×10^{-5}	1.2×10^{-4}	4.0×10^{-5}	1.0×10^{-4}

The calculated risks of lightning losses and their components are presented in Figures 2–4, simplified for particular components and zones.

**Figure 2.** Calculated values of risk of loss of human life R_1 and its components for the base case object (without protection measures).

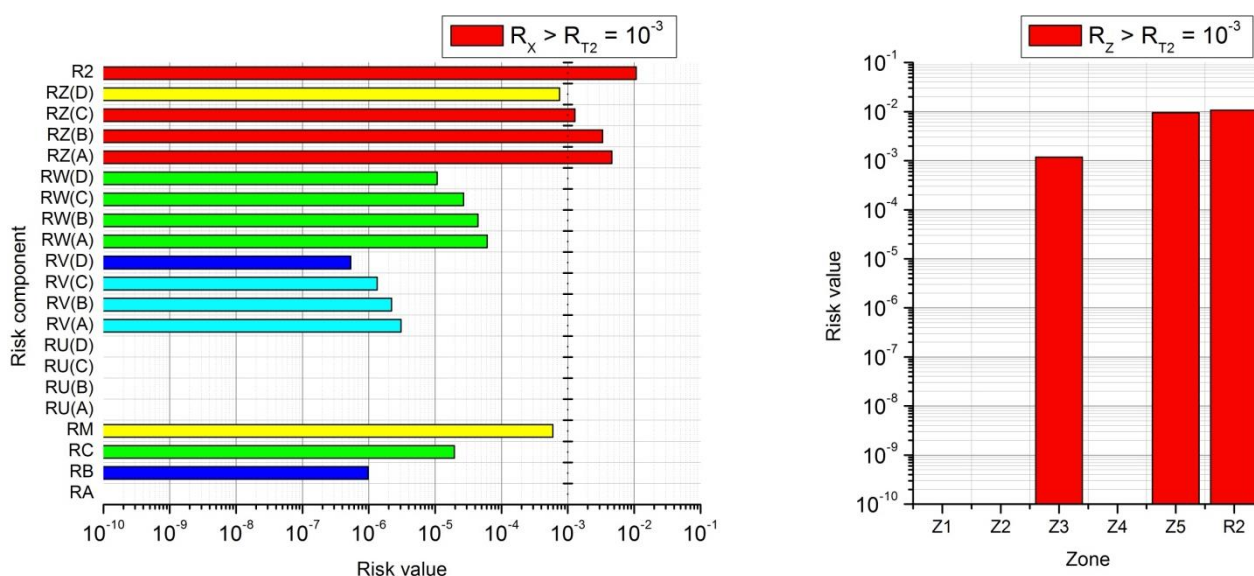


Figure 3. Calculated values of risk of loss of service to the public R_2 and its components for the base case object (without protection measures).

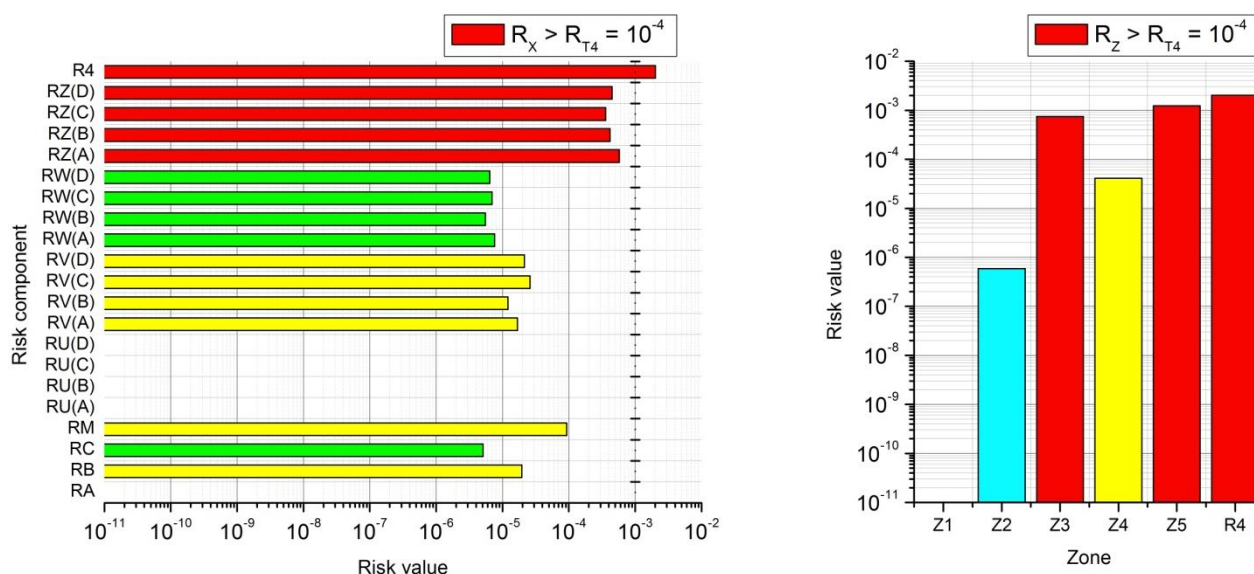


Figure 4. Calculated values of risk of loss of economic value R_4 and its components for the base case object (without protection measures).

The results show that the calculated risks of loss of human life R_1 , loss of service to the public R_2 , and loss of economic value R_4 are much higher than the tolerable values. Hence, the object requires the application of protection measures that would reduce the risks. Furthermore, the resulting values of particular risk components show which of them are the most relevant for the total values of the risks.

In the case of the risk of loss of human life, the most relevant are the risk components assigned to the environmental effects (components with subscript “E”, zone ZE) of failure of internal systems, i.e., a possible loss of life or permanent injury of people, being the consequence of failure or faulty operation of RTC system. Possibly all the risk components related to these effects except for R_{ME} (i.e., R_{WE} and R_{ZE} for all lines, and R_{CE}), may be relevant as compared with the tolerable value. Therefore, it is necessary to take provisions against failures of internal systems due to lightning flashes into and near the incoming

lines (to reduce R_{WE} and R_{ZE} for all lines) as well as into the object (to reduce R_{CE}). The values of the risk components in the zones of the object (Z1–Z5) are negligible.

For the risk of loss of service to the public, the most relevant are the risk components related to the failure of internal systems due to lightning flashes near the incoming lines (R_Z for all lines) and near the object (R_M). Other components can be regarded as irrelevant.

In case of the risk of economic value, similarly to the risk of loss of service to the public, the most relevant are the risk components related to the failure of internal systems due to lightning flashes near the incoming lines (R_Z for all lines) and near the object (R_M). However, it is not enough to reduce these components since even if reduced to 0, the total risk would be slightly higher than the tolerable value. Hence, in this case, it will be necessary to reduce also some less relevant components, i.e., related to the physical damage due to lightning flashes to incoming lines (R_V at least in some of the lines) and/or to the object (R_B).

3.2. Selection of Protection Measures and Its Characteristics—Object with Protection Measures

Based on the analysis of the calculated risk components the protection measures have been selected. Since for each considered type of risk, the sum of the components related to injuries (D1) and physical damage (D2), i.e., $R_A + R_B + R_U + R_V$, is below the tolerable value, the external lightning protection system (LPS) is not required [21]. Hence, equipotential bonding (EB) and coordinated surge protective devices (SPDs) were the primary choices of protection measures to be applied.

Using coordinated SPDs in all the internal systems connected to incoming lines reduces the probabilities of damage and thus reduces the risk components, as indicates (1). The reduction of probability is dependent on the lightning protection level (LPL) of the coordinated SPDs. The estimated values of probabilities for the coordinated SPDs of LPL III to IV are shown in Table 12.

Table 12. Estimated probabilities of damage for the object with coordinated SPDs of LPL III to IV.

Lightning Flashes:	Type of Damage	Symbol	Probability of Damage				
			Z1	Z2	Z3	Z4	Z5
To the object in concern	Injuries	P_A	1	1	1	1	1
	Physical damage	P_B	1	1	1	1	1
	Failure of internal systems	P_C	1	0	1	1	1
Near the object	Failure of internal systems	P_M	2.2×10^{-2}	1.0×10^{-8}	4.3×10^{-3}	3.2×10^{-4}	1.9×10^{-2}
To the lines incoming from direction A	Injuries	$P_{U(A)}$	0	0	0	0	5.0×10^{-4}
	Physical damage	$P_{V(A)}$	5.0×10^{-2}	0	0	0	5.0×10^{-2}
	Failure of internal systems	$P_{W(A)}$	5.0×10^{-2}	0	0	0	5.0×10^{-2}
Near the lines from direction A	Failure of internal systems	$P_{Z(A)}$	5.0×10^{-2}	0	0	0	5.0×10^{-2}
To the lines incoming from direction B	Injuries	$P_{U(B)}$	0	0	0	0	5.0×10^{-4}
	Physical damage	$P_{V(B)}$	5.0×10^{-2}	0	0	0	5.0×10^{-2}
	Failure of internal systems	$P_{W(B)}$	5.0×10^{-2}	0	0	0	5.0×10^{-2}
Near the lines from direction B	Failure of internal systems	$P_{Z(B)}$	5.0×10^{-2}	0	0	0	5.0×10^{-2}
To the lines incoming from direction C	Injuries	$P_{U(C)}$	0	0	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}
	Physical damage	$P_{V(C)}$	5.0×10^{-2}	0	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}
	Failure of internal systems	$P_{W(C)}$	5.0×10^{-2}	0	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}
Near the lines from direction C	Failure of internal systems	$P_{Z(C)}$	5.0×10^{-2}	0	5.0×10^{-2}	1.5×10^{-2}	3.0×10^{-2}
To the lines incoming from direction D	Injuries	$P_{U(D)}$	0	0	5.0×10^{-4}	0	0
	Physical damage	$P_{V(D)}$	5.0×10^{-2}	0	5.0×10^{-2}	0	0
	Failure of internal systems	$P_{W(D)}$	5.0×10^{-2}	0	5.0×10^{-2}	0	0
Near the lines from direction D	Failure of internal systems	$P_{Z(D)}$	5.0×10^{-2}	0	5.0×10^{-2}	0	0

The calculated values of risks for the object with coordinated SPD's in the internal systems connected to incoming external lines for different LPL are presented in Table 13,

together with the tolerable values of risks and indication of the required protection for each risk type.

Table 13. Calculated risks of losses for the object without protection and with coordinated SPDs of different LPL applied in all internal systems connected to the incoming lines.

	R₁: Risk of Loss of Human Life	R₂: Risk of Loss of Service to the Public	R₄: Risk of Loss of Economic Value
Tolerable risk value	1.0×10^{-5}	1.0×10^{-3}	1.0×10^{-4}
Without protection measures	5.37×10^{-4}	1.07×10^{-2}	2.02×10^{-3}
Coordinated SPDs of LPL III-IV	2.82×10^{-5}	5.61×10^{-4}	1.25×10^{-4}
Coordinated SPDs of LPL II	1.23×10^{-5}	2.37×10^{-4}	6.48×10^{-5}
Coordinated SPDs of LPL I	7.01×10^{-6}	1.29×10^{-4}	4.47×10^{-5}
Required protection measures	Coordinated SPDs of LPL I	Coordinated SPDs of LPL III-IV	Coordinated SPDs of LPL II

Coordinated SPDs of LPL III-IV allow reducing the risk of loss of service to the public below the tolerable value, however, the risks of loss of human life and loss of economic value are still too high. Reducing the risk of the loss of economic value below the tolerated value requires the coordinated SPDs of LPL II, and the risk of loss of human life—the coordinated SPDs of LPL I.

The risks of losses may also be reduced if the unshielded incoming external lines are replaced by shielded ones, as shown in Table 14 (bold font shows cases below the tolerable values).

Table 14. Calculated risks of losses for the object where unshielded incoming lines were replaced by shielded.

		R₁: Risk of Loss of Human Life	R₂: Risk of Loss of Service to the Public	R₄: Risk of Loss of Economic Value
	Tolerable risk value	1.0×10^{-5}	1.0×10^{-3}	1.0×10^{-4}
	Without protection measures	5.37×10^{-4}	1.07×10^{-2}	2.02×10^{-3}
Shielded incoming external lines	Shield not bonded to the same bonding bar as equipment	9.25×10^{-5}	1.91×10^{-3}	4.92×10^{-4}
	Shield bonded to the same bonding bar as equipment	8.74×10^{-6}	7.02×10^{-4}	1.73×10^{-4}
	Shield bonded to the same bonding bar as equipment + SPDs of LPL III-IV	6.45×10^{-6}	6.98×10^{-4}	1.35×10^{-4}
	Shield bonded to the same bonding bar as equipment + coordinated SPDs of LPL III-IV	2.09×10^{-6}	5.94×10^{-5}	3.27×10^{-5}

The results show that applying shielded incoming external lines allows one to reduce the risk of loss of human life and risk of loss of service to the public below the tolerable values, provided that the shield is bonded to the same bonding bar as internal equipment. Reducing the risk of loss of economic value below the tolerated level requires using in addition the coordinated surge protective devices (SPDs) of level III-IV (according to PN-

EN 62305-4). Using the SPDs only for the purpose of equipotential bonding (according to PN-EN 62306-3) is not enough.

4. Discussion

Safe and reliable operation of railway traffic control systems requires the application of proper protection measures against lightning electromagnetic pulse effects, otherwise, the consequences of damage to the system may be very serious. According to the standards on lightning protection PN-EN/EN 62305, the choice of protection measures must be based on the analysis of the risk of lightning losses. The standards, however, are not addressed to the railway objects. Moreover, there are no other regulations dedicated to the railway [21,28–30].

The performed analysis of lightning risk management for a case study railway object is an attempt of adopting the recommendations of the current standard PN-EN 62305-2:2012 for the analysis of risks of lightning losses and selection of lightning protection measures in certain types of objects of railway traffic control (RTC). In the risk analysis the following issues have been solved:

- Calculating the equivalent collection areas in the case when several lines incoming to the object follow the same or similar routes and selecting the worst case characteristics for estimation of probability parameters.
- Taking into account and evaluating the amount of loss of human life due to failures of RTC systems for people present in dangerous places outside the object. The typical mean value of loss L_{OE} was assumed as 10 times lower than for less significant parts of the hospital and the yearly time of presence of people in the dangerous places was taken as 1/3 of the year.
- Proposing the mean values of loss of public service due to physical damage and failures of RTC systems. The loss factors were assumed the same as for TV and telecommunication objects.
- Proposing the mean values of economic loss due to physical damage and failures of RTC systems. The loss factors were assumed near or lower as for industrial and commercial objects.
- Proposing the number of users served by the object, relevant to the loss of service to the public.
- Estimating the economic value of the object and its content relevant to the economic loss, according to PN-EN 62305-2:2012 using the lowest reference value for typical industrial structures.

Considering the fact that not very excessive parameters and characteristics were taken for the analysis, as described in Section 2, the calculated values of risk of all the types of losses in the object without protection measures are significantly higher than the tolerable values. High values of risks are mainly related to the failures of internal systems and physical damage due to lightning flashes into or near the incoming external lines. Hence, using an external lightning protection system (LPS) on the object is not efficient in reducing these risks. An efficient solution is the application of coordinated surge protective devices (SPDs) in all the internal systems connected to incoming lines.

The coordinated SPDs of the lowest lightning protection level (LPL III-IV) are, however, sufficient only for reducing the risk of loss of service to the public. For the other risks, the coordinated SPDs of better characteristics are required: in the case of the risk of economic losses, the coordinated SPDs of LPL II, and the case of risk of loss of human life the SPDs of LPL I. Hence, to attain complete protection, the coordinated SPDs of LPL I should be installed.

Another way to reduce the risks below the tolerable values is using shielded incoming external lines instead of unshielded ones. The lines shielding allows to reduce the risk of loss of human life and risk of loss of service to the public, however, it is effective only if the shields are connected to the same bonding bar as internal equipment. In the case of the risk of loss of economic value the shielding of lines together with proper bonding of the

shields at the entrance must be supplemented with coordinated surge protective devices of level III-IV.

Further directions of the research analysis can be related to including and valuation the amount of the loss of economic value, due to failures of RTC systems, in the case of damage to the property in dangerous places outside the object.

5. Conclusions

In the considered case of railway objects without protection measures, high values of risks have been obtained for all relevant types of loss, i.e., of human life, service to the public, and economic value. The calculated risks are much higher than the tolerable values.

The high risk of loss of human life is related mainly to people present outside the object, as being a consequence of failures of internal electrical and electronic systems of railway traffic control, which affect the railway automatic level crossings, remote signaling, and station equipment. The risks of loss of service to the public and loss of economic value are also basically caused by failures of internal systems. This is explained by the fact that sensitive electric and electronic internal systems must operate with a large number of various external lines (power, telecommunication, data), which are highly exposed to direct and nearby lightning flashes e.g., due to their significant length.

The practical solution that was considered to effectively reduce the risks was applying the coordinated surge protective devices (SPDs), which at the same time provide good equipotential bonding at the entry of the external lines to the object. Moreover, the values of risks of losses obtained in the object without and with protection using coordinated SPDs of different lightning protection levels (LPL) reveal that only using SPDs of sufficiently good parameters may reduce the risks below the tolerable values.

Other protection measures, whose application may be considered, are shielding of external lines and using buried lines instead of aerial. However, it should be noted that nearly all the external lines are underground and it would be very costly and inconvenient to replace the unshielded lines with shielded ones. Nevertheless, the obtained results show that the shielding of the incoming lines is effective in reducing the risk of loss of human life and risk of loss of service to the public only if the shields are bonded to the same bonding bar as internal equipment. For reducing the risk of economic value additional coordinated surge protective devices must be applied.

Taking into account that the risk calculations have been done for reliable, not very excessive input characteristics and parameters, the obtained results may be regarded as reasonable. Hence, the applied solutions and extensions, and the proposed input data characteristics may be used for managing the risks of lightning losses according to PN-EN 62305-2:2012 in the considered type of railway object. The developed calculation sheet is a useful tool for improving the risk management procedure.

Work is currently underway on a new edition of IEC 62305-2 (Ed 3), which will be based on the current general procedure of risk management. Work on the new edition of the standard aims to increase the accuracy of estimation of the risk of lightning losses, among others, by improving the procedure for assessing the density of lightning discharges using the latest data from lightning location systems. A ready-made spreadsheet will also be attached to the standard to facilitate calculations. As the more and more advanced electronic railway traffic control systems of greater sensitivity to impulse disturbances are used, it is important that the newly developed procedure and spreadsheet also included issues related to railway facilities.

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List of Symbols and Abbreviations

A_D (m^2)	equivalent collection area for lightning flashes to an isolated object (structure),
A_L (m^2)	equivalent collection area for lightning flashes to a line,
A_I (m^2)	equivalent collection area for lightning flashes near a line,
A_{DJ} (m^2)	equivalent collection area of direct lightning flashes to an adjacent structure,
A_M	equivalent collection area for lightning flashes striking near a structure,
c_a	value of the animals, in currency,
c_b	value of the building, in currency,
c_c	value of the content of an object, in currency,
C_D	location factor,
C_E	environmental factor,
C_{DJ}	location factor of an adjacent structure,
C_{LD}	factor depending on shielding, grounding, and isolation conditions of the line for lightning flashes to a line,
C_{LI}	factor depending on shielding, grounding, and isolation conditions of the line for lightning flashes near a line,
C_I	installation factor,
c_s	value of the internal systems (including their activities), in currency,
c_t	total value of a structure, in currency,
C_T	line type factor for an HV/LV transformer on the line,
D1	injury to living beings by electric shock,
D2	physical damage,
D3	failure of internal system,
EB	equipotential bonding,
EMC	Electromagnetic compatibility,
GPS	Global Positioning System,
H (m)	height of the structure,
h_z	factor increasing the loss when a special hazard is present,
K_{S1}	factor relevant to the screening effectiveness of the object,
K_{S2}	factor relevant to the screening effectiveness of shields internal to the object,
K_{S3}	factor relevant to the characteristics of internal wiring,
K_{S4}	factor relevant to the impulse withstand voltage of internal system,
L (m)	length of an object,
L_L (m)	length of a line,
L_1	loss of human life,
L_2	loss of service to the public,
L_3	loss of cultural heritage,
L_4	loss of economic value,
L_A	loss due to injury to living beings by electric shock (flashes to the object),
L_B	loss due to physical damage (flashes to the object),
L_C	loss related to failure of internal systems (flashes to the object),
L_M	loss related to failure of internal systems (flashes near the object),
L_F	typical mean amount of loss in a structure due to physical damage,
L_O	typical mean amount of loss in a structure due to failure of internal systems,
L_T	typical mean amount of loss in a structure due to injury by electric shock,

L_U	loss in a structure due to injury by electric shock (flashes to a line),
L_V	loss in a structure due to physical damage (flashes to a line),
L_W	loss in a structure due to failure of internal systems (flashes to a line),
L_Z	loss in a structure due to failure of internal systems (flashes near a line),
LINET (TOA)	Lightning Detection Network (Time-of-Arrival),
LPL	lightning protection level number related to a set of values of lightning current parameters relevant to the probability that the associated maximum and minimum design values will not be exceeded in naturally occurring lighting,
LPZ	lightning protection zone where the lightning electromagnetic environment is defined,
LPS	lightning protection system (complete system used to reduce physical damage due to lightning flashes to a structure),
N_D	number of dangerous events due to flashes to a structure (expected average annual number of dangerous events due to lightning flashes to a structure),
N_{DJ}	number of dangerous events due to flashes to an adjacent structure,
N_g	lightning ground flash density (number of lightning discharges to ground per square kilometer per year),
N_I	number of dangerous events due to flashes near a line,
N_L	number of dangerous events due to flashes to a line,
N_M	number of dangerous events due to flashes near a structure,
NTL	non-traction line,
n_t	expected total number of persons (or users served),
n_z	number of possible endangered persons (victims or users not served),
P_A	probability of injury to living beings by electric shock (flashes to a structure),
P_B	probability of physical damage to a structure (flashes to a structure),
P_C	probability of failure of internal systems (flashes to a structure),
P_{LD}	probability reducing P_U , P_V , and P_W depending on line characteristics and withstand voltage of equipment (flashes to a line),
P_{LI}	probability reducing P_Z depending on line characteristics and withstand voltage of equipment (flashes near a line),
P_U	probability of injury to living beings by electric shock (flashes to a line),
P_V	probability of physical damage to a structure (flashes to a line),
P_W	probability of failure of internal systems (flashes to line),
P_Z	probability of failure of internal systems (flashes near a line),
R_1	risk of loss of human life in a structure,
R_2	risk of loss of service to the public,
R_3	risk of loss of cultural heritage,
R_4	risk of loss of economic value,
R_A	risk component (injury to living beings—flashes to a structure),
R_B	risk component (physical damage to a structure—flashes to a structure),
R_C	risk component (failure of internal systems—flashes to a structure),
R_{CE}	risk components related to environmental effects of damage in an object, i.e., outside the object (failure of internal systems—flashes to a structure),
r_f	factor reducing loss depending on the risk of fire,
R_M	risk component (failure of internal systems—flashes near a structure),
R_{ME}	risk components related to environmental effects of damage in an object, i.e., outside the object (failure of internal systems—flashes near a structure),
r_p	factor reducing the loss due to provisions against fire,
r_t	factor reducing the loss, associated with the type of surface,
R_T	tolerable risk—maximum value of the risk which can be tolerated for the structure to be protected,
R_U	risk component (injury to a living being—flashes to a line),
R_V	risk component (physical damage to the structure—flashes to a line),
R_W	risk components (failure of internal systems—flashes to a line),
R_{WE}	risk components related to environmental effects of damage in an object, i.e., outside the object (failure of internal systems—flashes to a line),

R_Z	risk component (failure of internal systems—flashes near a line),
R_{ZE}	risk components related to environmental effects of damage in an object, i.e., outside the object (failure of internal systems—flashes near a line),
RTC	railway traffic control,
SPD	surge protective device,
TLC	telecommunication (line lines intended for communication between equipment that may be located in separate structures, such as phone lines and data lines),
t_e	time in hours per year of the presence of people in a dangerous place outside the structure,
t_z	time in hours per year that persons are present in a dangerous place in the structure,
U_W	impulse withstand voltage assigned by the manufacturer to the equipment or a part of it characterizing the specified withstand capability of its insulation against transient overvoltages,
W (m)	width of a structure,
Z1	zone of the object around the signal box, access from the ground,
Z2	zone of the object around the antenna mast, access from the roof of the signal box,
Z3	zone of the object—section inspector duty room,
Z4	zone of the object—repair workshop room,
Z5	zone of the object—relay room,
ZE	zone outside the object where environmental effects of damage in the object may occur.

Appendix A

The characteristics of the object and incoming lines, which were used to determine the numbers of dangerous events N_X according to formula (1) and Table 1, are shown in Tables A1–A11.

Table A1. Properties of the object to be protected (signal box with aerial antenna mast on the roof).

Parameter	Symbol	Value (Property)
Physical dimensions	$L; W; H; H_{\max}$ (m)	14; 10; 8; 16
Equivalent collection area of direct flashes	A_D (m ²)	7238
Location factor	C_D (-)	1 (Isolated)
Equivalent collection area of near flashes	A_M (m ²)	809,398

Table A2. Properties of the feeding line 230/400 V.

Parameter	Symbol	Value (Property)
Length	L_L (m)	1000
Collection area of direct flashes	A_L (m ²)	40,000
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Low voltage power)
Environmental factor	C_E (-)	0.5 (Suburban)
Collection area of near flashes	A_I (m ²)	4,000,000
Structure at the opposite end of the line (MV/LV station):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	1 (Isolated)

Table A3. Properties of the telephone line 1.

Parameter	Symbol	Value (Property)
Length	L_L (m)	1000
Collection area of direct flashes	A_L (m ²)	40,000
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Telecommunication)
Environmental factor	C_E (-)	0.5 (Suburban)
Collection area of near flashes	A_I (m ²)	4,000,000
Structure at the opposite end of the line (local exchange):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	1 (Isolated)

Table A4. Properties of the telephone line 2.

Parameter	Symbol	Value (Property)
Length	L_L (m)	1000
Collection area of direct flashes	A_L (m ²)	40,000
Installation factor	C_I (-)	1 (Aerial)
Line type factor	C_T (-)	1 (Telecommunication)
Environmental factor	C_E (-)	0.5 (Suburban)
Collection area of near flashes	A_I (m ²)	4,000,000
Structure at the opposite end of the line (local exchange):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	1 (Isolated)

Table A5. Properties of the feeding line 230/500 V to the voltage box (RS).

Parameter	Symbol	Value (Property)
Length	L_L (m)	30
Collection area of direct flashes	A_L (m ²)	1200
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Low voltage power)
Environmental factor	C_E (-)	0.5 (Suburban)
Collection area of near flashes	A_I (m ²)	120,000
Structure at the opposite end of the line (voltage box):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	0.25 (Surrounded by higher objects)

Table A6. Properties of the feeding line 230/500 V (line 1 for direction A and line 2 for direction B).

Parameter	Symbol	Value (Property)
Length	L_L (m)	1000
Collection area of direct flashes	A_L (m ²)	40,000
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Low voltage power)
Environmental factor	C_E (-)	1 (Rural)
Collection area of near flashes	A_I (m ²)	4,000,000
Structure at the opposite end of the line (supplied system):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	1 (Isolated)

Table A7. Properties of the control line to the automatic level crossing 1.

Parameter	Symbol	Value (Property)
Length	L_L (m)	30
Collection area of direct flashes	A_L (m ²)	1200
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Data)
Environmental factor	C_E (-)	0.5 (Suburban)
Collection area of near flashes	A_I (m ²)	120,000
Structure at the opposite end of the line (crossing 1):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	0.25 (Surrounded by higher objects)

Table A8. Properties of the control line to the automatic level crossing 2.

Parameter	Symbol	Value (Property)
Length	L_L (m)	1420
Collection area of direct flashes	A_L (m ²)	56,800
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Data)
Environmental factor	C_E (-)	1 (Rural)
Collection area of near flashes	A_I (m ²)	5,680,000
Structure at the opposite end of the line (crossing 2):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	1 (Isolated)

Table A9. Properties of the control line to the automatic level crossing 3.

Parameter	Symbol	Value (Property)
Length	L_L (m)	685
Collection area of direct flashes	A_L (m ²)	27,400
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Data)
Environmental factor	C_E (-)	1 (Rural)
Collection area of near flashes	A_I (m ²)	2,740,000
Structure at the opposite end of the line (crossing 3):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	1 (Isolated)

Table A10. Properties of the signal line to station equipment.

Parameter	Symbol	Value (Property)
Length	L_L (m)	1000
Collection area of direct flashes	A_L (m ²)	40,000
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Data)
Environmental factor	C_E (-)	1 (Rural)
Collection area of near flashes	A_I (m ²)	4,000,000
Structure at the opposite end of the line (station equipment):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	1 (Isolated)

Table A11. Properties of the signal lines for remote signaling: line 1 (direction A) line 2 (direction B).

Parameter	Symbol	Value (Property)
Length	L_L (m)	1000
Collection area of direct flashes	A_L (m ²)	40,000
Installation factor	C_I (-)	0.5 (Buried)
Line type factor	C_T (-)	1 (Data)
Environmental factor	C_E (-)	1 (Rural)
Collection area of near flashes	A_I (m ²)	4,000,000
Structure at the opposite end of the line (signaling equipment):		
Physical dimensions	$L; W; H; H_{\max}$ (m)	0; 0; 0; 0
Collection area of direct flashes	A_{DJ} (m ²)	0
Location factor	C_{DJ} (-)	1 (Isolated)

Appendix B

The specific characteristics of the object (signal box), incoming external lines, internal electrical and electronic systems installed in the object, and applied protection measures against electric shock, lightning, and overvoltage, that are needed to determine the values of probabilities of damage P_X (formulas: (1) and in Table 1), are presented in Tables A12–A15.

Table A12. Characteristics of the object (signal box with antenna mast) affecting the probabilities of damage.

Property	Parameter	Characteristics				
		Z1	Z2	Z3	Z4	Z5
Lightning protection system (LPS)	P_B	No protection	No protection	No protection	No protection	No protection
Protection against electric shock due to a direct lightning flash	P_{TA}	No protection	No protection	No protection	No protection	No protection
Screening effectiveness of the structure at the boundary LPZ 0/1	K_{S1}	No shielding	No shielding	No shielding	No shielding	No shielding
Screening effectiveness of internal shields, i.e. within LPZ 1	K_{S2}	No shielding	No shielding	No shielding	No shielding	No shielding

Table A13. Characteristics of the incoming lines to which the internal systems are connected.

Internal System	Zones where Internal System Extends	C_{LD}, C_{LI}, P_{LD}		P_{LD}	P_{LI}
		Shielding, Grounding, and Isolation Conditions of the Incoming Line		Resistance R_S of the Shield (Ω/km)	Line Type
		Line Type	Connection at Entrance		
Antenna	Z2, Z3	Aerial, shielded	No connection (internal line)	(5; 20)	Telecom
Power 230/400 V	Z1, Z3, Z4, Z5	Buried, unshielded			Power
Power 230/500 V	Z1, Z5	Buried, unshielded			Power
Telecommunication 1	Z1, Z3	Buried, unshielded			Telecom
Telecommunication 2	Z1, Z3	Aerial, unshielded			Telecom
Control of crossing 1	Z1, Z5	Buried, unshielded			Telecom
Control of crossing 2	Z1, Z5	Buried, unshielded			Telecom
Control of crossing 3	Z1, Z5	Buried, unshielded			Telecom
Station equipment	Z1, Z5	Buried, unshielded			Telecom
Signaling 1	Z1, Z5	Buried, unshielded			Telecom
Signaling 2	Z1, Z5	Buried, unshielded			Telecom

Table A14. Characteristics of the internal systems within the object.

a. Type of internal wiring.					
Internal System	K_{S3}				
	Type of Internal Wiring of the System				
	Z1	Z2	Z3	Z4	Z5
Antenna	-	Shielded	Shielded	-	-
Power 230/400 V	Unshielded, route avoiding large loops	-	Unshielded, route avoiding large loops	Unshielded, route avoiding large loops	Unshielded, route avoiding large loops
Power 230/500 V	Unshielded, route avoiding large loops	-	-	-	Unshielded, route avoiding large loops
Telecom. 1	Unshielded, route avoiding large loops	-	Unshielded, route avoiding large loops	-	-
Telecom. 2	Unshielded, route avoiding large loops	-	Unshielded, route avoiding large loops	-	-
Control of crossing 1	Unshielded, route avoiding large loops	-	-	-	Unshielded, route avoiding large loops
Control of crossing 2	Unshielded, route avoiding large loops	-	-	-	Unshielded, route avoiding large loops
Control of crossing 3	Unshielded, route avoiding large loops	-	-	-	Unshielded, route avoiding large loops
Station equipment	Unshielded, route avoiding large loops	-	-	-	Unshielded, route avoiding large loops
Signaling 1	Unshielded, route avoiding large loops	-	-	-	Unshielded, route avoiding large loops
Signaling 2	Unshielded, route avoiding large loops	-	-	-	Unshielded, route avoiding large loops
b. Impulse withstand voltage.					
Internal System	K_{S4}, P_{LD}, P_{LI}				
	Lowest Impulse Withstand Voltage U_W (kV)				
	Z1	Z2	Z3	Z4	Z5
Antenna	-	1.0	1.0	-	-
Power 230/400 V	2.5	-	2.5	2.5	1.5
Power 230/500 V	1.0	-	-	-	1.0
Telecommunication 1	1.0	-	1.0	-	-
Telecommunication 2	1.0	-	1.0	-	-
Control of crossing 1	1.0	-	-	-	1.0
Control of crossing 2	1.0	-	-	-	1.0
Control of crossing 3	1.0	-	-	-	1.0
Station equipment	1.0	-	-	-	1.0
Signaling 1	1.0	-	-	-	1.0
Signaling 2	1.0	-	-	-	1.0

Table A15. Characteristics of the protection measures in the internal systems within the object.

a. Protection against electric shock.					
Internal System	P _{TU}				
	Protection against Electric Shock Due to the Flash to the Incoming Line				
	Z1	Z2	Z3	Z4	Z5
Antenna	-	Electrical insulation, physical restrictions	Electrical insulation	-	-
Power 230/400 V	Electrical insulation, physical restrictions	-	Electrical insulation	Electrical insulation	Electrical insulation
Power 230/500 V	Electrical insulation, physical restrictions	-	-	-	Electrical insulation
Telecom. 1	Electrical insulation, physical restrictions	-	Electrical insulation	-	-
Telecom. 2	Electrical insulation, physical restrictions	-	Electrical insulation	-	-
Control of crossing 1	Electrical insulation, physical restrictions	-	-	-	Electrical insulation
Control of crossing 2	Electrical insulation, physical restrictions	-	-	-	Electrical insulation
Control of crossing 3	Electrical insulation, physical restrictions	-	-	-	Electrical insulation
Station equipment	Electrical insulation, physical restrictions	-	-	-	Electrical insulation
Signaling 1	Electrical insulation, physical restrictions	-	-	-	Electrical insulation
Signaling 2	Electrical insulation, physical restrictions	-	-	-	Electrical insulation
b. Coordinated surge protective devices.					
Internal System	P _{SPD}				
	Coordinated Surge Protective Devices (SPD's) in the Internal System				
	Z1	Z2	Z3	Z4	Z5
Antenna	-	No coordinated SPDs	No coordinated SPDs	-	-
Power 230/400 V	No coordinated SPDs	-	No coordinated SPDs	No coordinated SPDs	No coordinated SPDs
Power 230/500 V	No coordinated SPDs	-	-	-	No coordinated SPDs
Telecom. 1	No coordinated SPDs	-	No coordinated SPDs	-	-
Telecom. 2	No coordinated SPDs	-	No coordinated SPDs	-	-
Control of crossing 1	No coordinated SPDs	-	-	-	No coordinated SPDs
Control of crossing 2	No coordinated SPDs	-	-	-	No coordinated SPDs
Control of crossing 3	No coordinated SPDs	-	-	-	No coordinated SPDs
Station equipment	No coordinated SPDs	-	-	-	No coordinated SPDs
Signaling 1	No coordinated SPDs	-	-	-	No coordinated SPDs
Signaling 2	No coordinated SPDs	-	-	-	No coordinated SPDs

Table A15. Cont.

c. Equipotential bonding.					
Internal System	P_{EB}				
	Equipotential Bonding Provided by SPD at the Entry of the Incoming Line				
	Z1	Z2	Z3	Z4	Z5
Antenna	-	No SPD	No SPD	-	-
Power 230/400 V	No SPD	-	No SPD	No SPD	No SPD
Power 230/500 V	No SPD	-	-	-	No SPD
Telecom. 1	No SPD	-	No SPD	-	No SPD
Telecom. 2	No SPD	-	No SPD	-	No SPD
Control of crossing 1	No SPD	-	-	-	No SPD
Control of crossing 2	No SPD	-	-	-	No SPD
Control of crossing 3	No SPD	-	-	-	No SPD
Station equipment	No SPD	-	-	-	No SPD
Signaling 1	No SPD	-	-	-	No SPD
Signaling 2	No SPD	-	-	-	No SPD

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