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Research paper

Safety at railway level crossings and Vision Zero

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Abstract: In this work, safety analysis at the railway level crossings is presented using advanced mathematical modelling. Resistivity of track subgrade panels is taken into account. The analysis does not refer to the assessment of the current regulations. Specific cases of generalized dynamic system are considered by introducing operations $S=\Delta$, $S=P$ defined in space C(N) of real sequences. In this model, generalized discrete exponential and trigonometric functions that reflect the oscillatory nature of the analysed quantities are used. The advantage of the analyzes is the avoidance of numerical errors. We show also the importance of the resistivity of track subgrade panels in safety at the level crossings. The safety at the level crossings can be increased through providing track subgrade panels with appropriate resistivity to minimize negative effect of stray currents. The results may be used to evaluate selected safety indicators as well as to predict safety levels and to determine the ways of improving safety.

Keywords: safety, railway level crossings, non-classical operational calculus, resistivity

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1. Introduction

The intersection of a railway line with a road can have the a form of one- or two-level structure. In the first case, the intersection can be called railway level crossing or simply level crossing. Contemporary scientific literature addresses the issues of behavior of drivers or train drivers [2] as well as driver education [18]. The documents of the European Railway Agency or the Polish Office of Rail Transport present mainly the statistical data [2, 3, 12]. Another important direction of studies in the last years is the modeling of safety systems at railway crossings in terms of risk management and risk model development [1, 8, 9, 19, 20].

Level crossings belong to the spots exposed to collisions causing significant material damage and often victims. For example, 215 accidents, with 49 people killed and 33 seriously injured, occurred on 12801 level crossings in a public and isolated railway networks in 2018 [12].

Safety at level crossings is an element of the entire transport safety system, which aims at maximum reducing of accidents at level crossings. In-depth analysis, in particular the development of an advanced analytical model, is required.

According to [11], level crossings can only be used on rail lines where the traffic speed does not exceed 160 km/h. In other cases, two-level intersections are used.

It has to be noted that the accidents can happen even at the two-level intersections, which impacts both road and railway safety. The photo in Fig. 1 presents the tanker that fell down from the viaduct to the railway area, thus creating a danger in both road and rail traffic.

Fig. 1. A 20-tone tanker fallen from the viaduct over the railroad (line #201) at the stop of Podleś. The tanker transported propane-butane gas [8]

The concept of traffic product defined as the product of the number of road vehicles and trains crossing the level crossing during 24 hours is introduced in [11]. The value of traffic product determines the qualification of a given crossing into one of the categories: A, B, C, D, E, F. In [11], it was also specified how often traffic (rail and road traffic) measurements should be performed at the level crossing. As an example, category B includes rail-road crossings as intersections of railway lines or railway sidings with public roads, where:

a) the traffic product is equal at least 150 000 or
b) a railway line or railway siding crosses a national road.

When determining the traffic product, the isolated points with natural coordinates appear on the hyperbolic paraboloid, which in this case is a symmetrical function of n = 2 variables because for any n n-element series of arguments it gives the same value as for any permutation of this series of arguments from a given set Ω. This is a similar property as for the scalar product in real domain. The property noted here means that the traffic product used for determining the category of level crossing is not perfect and not objective and may lead to incorrect qualifications of level crossing.

According to [11], the category of rail-road crossing or crossing and the way it is secured is determined by the railway managing party. This is related to the way traffic is controlled at the crossing and the controlling devices (Table 1). As of December 31, 2018, there were 12801 level crossings on active railway lines, including 489 crossings (category E) [16].

Tab. 1. Information on level crossings [16]

Category of level crossing	Method of directing traffic at a railroad crossing	Device for traffic control	Number of level crossings*) (updated on Dec 31, 2018)
A	Authorized employees of the railway manager or railway operator with required qualifications (gateman / signalman)	Manual traffic control devices, full-length barriers, traffic signal devices.	2415
B	Automatic systems.	Traffic signal devices, half-barriers	1270
C	Automatic systems	Traffic signal devices	1431
D	No traffic control systems	No systems or devices for traffic control	6580
E*)	No traffic control systems or automatic or semiautomatic systems.	Gates, pedestrian mazes etc.	489

F	Barriers are constantly closed. Barriers can be opened by the users or under the conditions for category A or B.	Barriers constantly closed.	616
A	Authorized employees of the railway manager or railway operator with required qualifications (gateman / signalman)	Manual traffic control devices, full-length barriers, traffic signal devices.	2415
*) including bike traffic			

Safety levels at the level crossings are related to the provisions of Art. 6 of the Directive 2004/49/EC of the European Parliament in order to achieve common goals and methods of safety assessment, which is indicated as Common Safety Target (CST) and Common Safety Method (CSM). The European Railway Agency (EAR) refers the safety levels to the National Reference Values (NRV) established on June 5, 2009, for individual countries. NRV in Poland for level crossing users was set at $277 \cdot 10^{-9}$ - for fatalities and weighted seriously injured people per billion train-kilometers. The method of determining this value can raise many justified doubts. The Agency considers that, as with any statistical method, the results obtained through this assessment, should be used with caution. In particular, the Agency recognizes:

- a limitation in the data used for establishment of NRV5 and for their assessment;
- the need to update the NRV5 used for the assessment;
- the difficulty of using the Method in relation to categories involving small numbers of fatalities, and
- the method is not to be used for proactive safety analysis.

The Agency has conducted a consultation to support revision of the Method whose outcome was to continue with the present method with an updating of NRVs [7].

The aim of this study is to demonstrate the possibility of transport system modeling in the form of a generalized dynamical system in order to avoid errors of numerical modeling. The presented approach will allow for proper intervention in the system to improve its safety parameters. We will also present the system for determination of the resistivity of the level crossing and track subgrade panels since the impact of stray currents on the infrastructure is still an important element limiting the reliability of level crossing control elements.

2. Discrete model

The transportation system as a whole, or its subsystems like road, rail, air or water transportation systems - can be considered as a generalized dynamic system. The model is by a set of relationships linking the impact of the system on the environment and vice versa [7, 9]. Such information enables controlling the system or correcting its operation by a feedback control. The theories and modeling make it easier to understand the processes that occur in road traffic, including the traffic at the level crossings. They also help in determining the cause of accidents in the critical spots on the rail and road network.

Special cases of generalized dynamical systems based on non-classical operational calculus will be used for modeling. A set of linear spaces L^0, L^1 ($L^1 \subset L^0$) along with linear operations S, T_q, s_q or S, T, s associated with them are fundamental for non-classical operational calculus (S - derivative, T_q - antiderivative of a function, s_q – border condition) [9, 10].

In the theory of non-classical operational calculus, iteration of operation S can be expressed by the iteration of the generalized Heaviside operator p_q and its action on the elements from the kernel S ($KerS$). This can be written as:

$$S^n x = p_q^n x - p_q^n x_{0,q} - p_q^{n-1} x_{1,q} - \cdots - p_q x_{n-1,q} \tag{2.1}$$

where:

$$x \in L^n = \{x \in L^{n-1} : Sx \in L^{n-1}\} , \ n = 2, 3, 4, \dots ,$$

$$x_{i,q} = s_q S^i x \in KerS , \quad i = 0, 1, \dots, n-1.$$

n – is the rank of the space L^n

Adopting an appropriate representation of operational calculus leads to continuous or discrete models. In the case of generalized dynamical systems, this leads to classical continuous or discrete dynamic systems with concentrated or distributed parameters [10]. For discrete systems, the most commonly used operations are:

$$S = \Delta \text{ or } S = P \text{ (differential derivatives).}$$

Both operations are defined in the space $L^0 = C(N)$ of real sequences by the following equations:

$$\Delta\{x_k\} = \{x_{k+1} - x_k\}, \quad P\{x_k\} = \{x_{k+1}\} , \quad \{x_k\} \in C(N).$$

(One can write also $x_k \in C(N)$. However, this notation is not precise.)

The advantage of implementing a discrete model is that $L^0 = L^i$, $i = 1, 2, 3, \dots, n$ for both models.

The apparatus of the non-classical operator calculus facilitates operator analysis by enabling determination the operator response based on the basic elements of the above-mentioned spaces [9, 10]. These are key elements since they represent characteristics of the analyzed dynamical systems, also in relation to the recorded: number of accidents at level crossings, to the number of fatalities and seriously injured, to the number of road users involved in rail accidents (categorized as drivers of passenger cars and pedestrians) – Figs. 2-4.

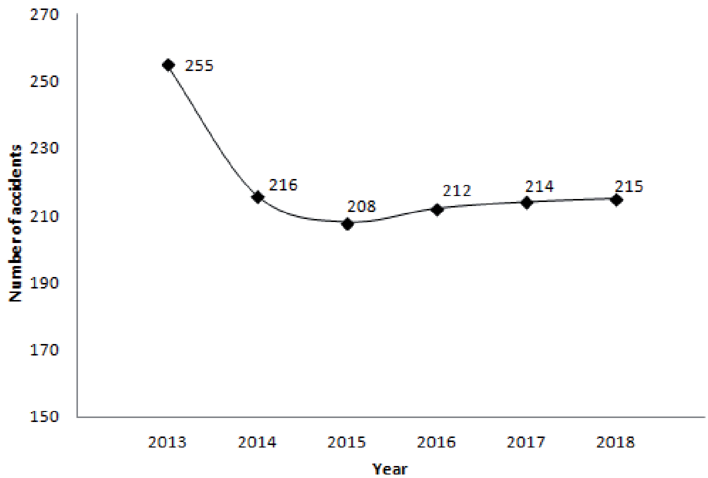

Fig. 2. Number of accidents at level crossings. Own study based on [12]

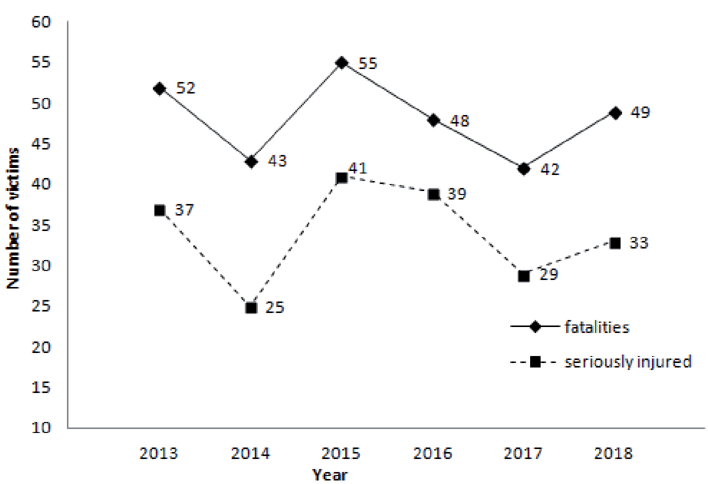

Fig. 3. Number of fatalities and seriously injured at level crossings. Own study based on [12]

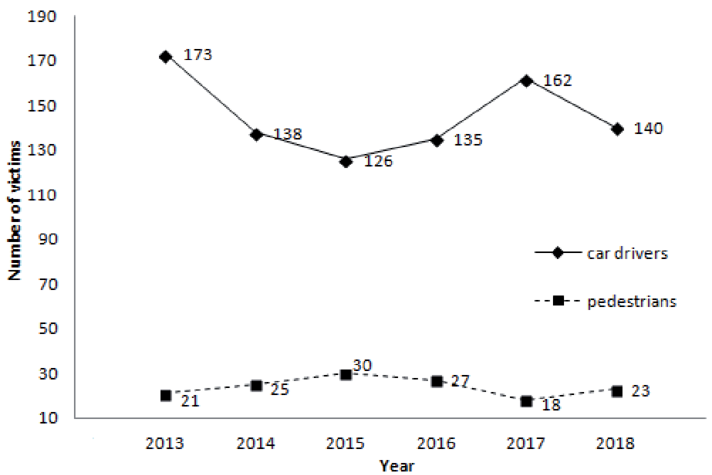

Fig. 4. Number of road users involved in rail accidents (drivers and pedestrians). Own study based on [12]

In this model, generalized discrete exponential and trigonometric functions [10] that reflect the oscillatory nature of the analyzed quantities are of key importance (Figs. 5-6). In the figures shown below, x_k indicates a sequence with the elements x_k, where $k = 0, 1, 2, ...$

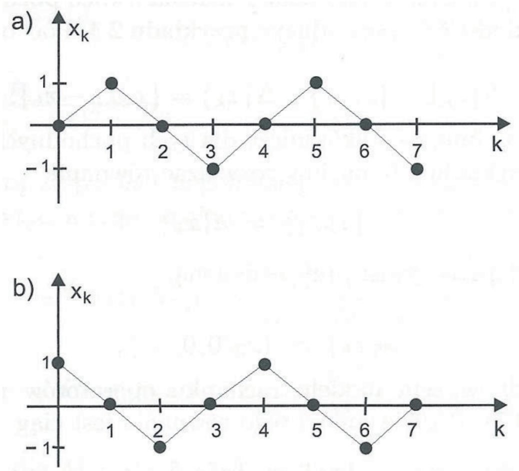

Fig. 5. Graphs of generalized functions a) $\sin t_q s\{1\}$, b) $\cos t_q s\{1\}$ for $S = P$

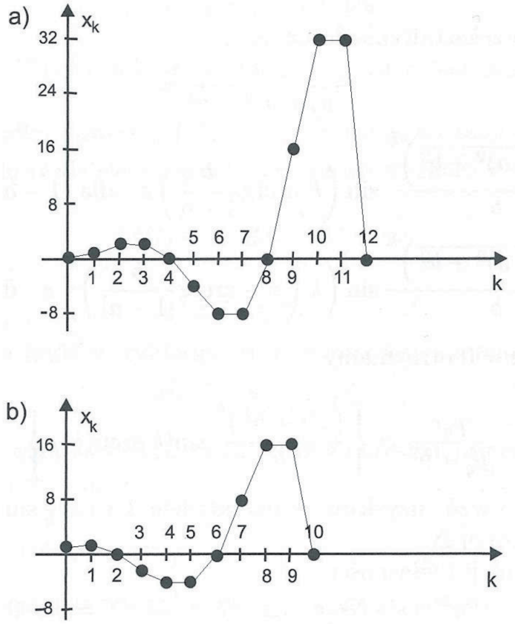

Fig. 6. Graphs of generalized functions a) $\sin t_q\{1\}$, b) $\cos t_q\{1\}$ for $S = \Delta$

The generalized discrete trigonometric functions shown in Figures 5 and 6 are, respectively, special cases of discrete functions of the form:

(2.2) $$\sin t_q s\,\{x_k\} = \left\{x_0 \sin k\,\tfrac{\pi}{2}\right\}, \quad \cos t_q s\{x_k\} = \left\{x_0 \cos k\,\tfrac{\pi}{2}\right\},$$

(2.3) $$\sin at_q\,\{x_0\} = \left\{\left(\sqrt{1+a^2}\right)^k \sin(k\,arctga)\,x_0\right\},$$

(2.4) $$\cos at_q\{x_0\} = \left\{(\sqrt{1+a^2})^k \cos(k\,arctga)x_0\right\},$$

where: a is set value.

Functions (2.2), (2.3) and (2.4) are expressed by the generalized discrete exponential functions [10]:

(2.5) $$e^{at_q}s\{x_k\} = \{a^k x_0\}, \quad e^{at_q}\{x_0\} = \{(1+a)^k x_0\}.$$

Figure 2 shows the behavior of a discrete dynamic system. This system can be modelled by differential equations. We can obtain a differential equation describing the number of accidents at level crossings in 2013-2018 based on the principles presented in [6]:

$$\Delta^6 x + 6\Delta^5 x + 11\Delta^4 x + 4\Delta^3 x - 10\Delta^2 x - 12\Delta x - 3x = 0. \tag{2.6}$$

where:

$$x = \{x_k\} \in C(N)$$

Equation (6) can be written in a less precise form as:

$$\Delta^6 x_k + 6\Delta^5 x_k + 11\Delta^4 x_k + 4\Delta^3 x_k - 10\Delta^2 x_k - 12\Delta x_k - 3x_k = 0. \tag{2.7}$$

The relationship in Eq. (2.1) allows for determination of the responses of generalized dynamical systems. The procedure has been described in [10] and will be further used to determine the response of the dynamic system describing the number of accidents at level crossings in 2013-2018.

Applying Eq. (2.1) to Eq. (2.6) and (2.7), we can obtain:

$$p_q^6 x - p_q^6 x_{0,q} - p_q^5 x_{1,q} - p_q^4 x_{2,q} - p_q^3 x_{3.q} - p_q^2 x_{4,q} - p_q x_{5,q} +$$

$$+6(p_q^5 x - p_q^5 x_{0,q} - p_q^4 x_{1,q} - p_q^3 x_{2,q} - p_q^2 x_{3.q} - p_q x_{4,q}) +$$

$$+11\left(p_q^4 x - p_q^4 x_{0,q} - p_q^3 x_{1,q} - p_q^2 x_{2,q} - p_q x_{3,q}\right) + 4\left(p_q^3 x - p_q^3 x_{0,q} - p_q^2 x_{1,q} - p_q x_{2,q}\right) -$$

$$-10(p_q^2 x - p_q^2 x_{0,q} - p_q x_{1,q}) - 12(p_q x - p_q x_{0,q}) - 3x = 0,$$

where:

$x = \{x_k\} \in C(N)$ and $x_{i,q} \in Ker\Delta$, *i* = 1, 2, 3, 4, 5.

From the last equation we have:

$$(p_q^6 + 6p_q^5 + 11p_q^4 + 4p_q^3 - 10p_q^2 - 12p_q - 3id)x =$$

$$= p_q^6 x_{0,q} + 6p_q^5 x_{0,q} + 11p_q^4 x_{0,q} + 4p_q^3 x_{0,q} - 10p_q^2 x_{0,q} - 12p_q x_{0,q} +$$

$$+p_q^5 x_{1,q} + 6p_q^4 x_{1,q} + 11p_q^3 x_{1,q} + 4p_q^2 x_{1,q} - 10p_q x_{1,q} +$$

$$+p_q^4x_{2,q}+6p_q^3x_{2,q}+11p_q^2x_{2,q}+4p_qx_{2,q}+$$

$$+p_q^3x_{3.q}+6p_q^2x_{3.q}+11p_qx_{3,q}+p_q^2x_{4,q}+6p_qx_{4,q}+p_qx_{5,q}.$$

The solution, i.e. the response of the system (2.6) and (2.7) in the operator notation is given by:

$$x=\frac{p_q^6+6p_q^5+11p_q^4+4p_q^3-10p_q^2-12p_q}{p_q^6+6p_q^5+11p_q^4\ +4p_q^3-10p_q^2-12p_q-3id}x_{0,q}+$$

$$+\frac{p_q^5+6p_q^4+11p_q^3+4p_q^2-10p_q}{p_q^6+6p_q^5+11p_q^4\ +4p_q^3-10p_q^2-12p_q-3id}x_{1,q}+$$

$$+\frac{p_q^4+6p_q^3+11p_q^2+4p_q}{p_q^6+6p_q^5+11p_q^4\ +4p_q^3-10p_q^2-12p_q-3id}x_{2,q}+$$

$$+\frac{p_q^3+6p_q^2+11p_q}{p_q^6+6p_q^5+11p_q^4\ +4p_q^3-10p_q^2-12p_q-3id}x_{3,q}+$$

$$+\frac{p_q^2+6p_q}{p_q^6+6p_q^5+11p_q^4\ +4p_q^3-10p_q^2-12p_q-3id}x_{4,q}+$$

$$+\frac{p_q}{p_q^6+6p_q^5+11p_q^4\ +4p_q^3-10p_q^2-12p_q-3id}x_{5,q}$$

The analysis of the dynamic system (2.6) or (2.7) can be performed by the model in non-classical operator calculus with the operation $S = P$. In this case, Heaviside operator is associated with the operation $S = P$, and to be more precise with the corresponding operation T_q. Then, Eq. (2.6) must also be written using the operation P.

Each component of the last expression is a rational function of the Heaviside operator acting on the elements $x_{i,q} \in Ker\Delta\ \left(x_{i,q} \in KerP\right)$, i =1, 2, 3, 4, 5. Then, according to the Haeviside's theorem [10], those components can be expressed using generalized exponential or trigonometric functions. These are discrete functions of special shapes described by Eqs. (2.2)-(2.5) and shown already in Figs. 5-6.

Using Heaviside's theorem and formulas (2.2)-(2.5), the selected solution of the dynamical system (2.6) and (2.7) can be written as a sequence:

$$\{x_k\}=\left\{226{,}25-1{,}38\ 2^k+12{,}08\ (-1)^k-1{,}35\ (-2)^k+19{,}41\ cosk\frac{\pi}{2}+1{,}91\ sink\frac{\pi}{2}\right\}$$

It is crucial that analytical, not numerical approach was used to calculate the response of the system. Following the same procedure, we can develop dynamic models for the cases shown in Figs. 3-4 and write differential equations describing the relationships.

3. Resistivity of the module of level crossing

The safety at the level crossings can be increased through providing track subgrade panels with appropriate resistivity to minimize negative effect of stray currents.

The rails laid on track subgrade panels (Fig. 7) cannot be completely insulated from the ground. Therefore, the traction current flowing through the rails cannot be completely directed to the ground, which generates so-called stray currents. The contact resistance of the rail-ground interface depends on the method of construction and the design of the railway surface (e.g. ballastless pavement), the type of subgrade and atmospheric conditions (i.e. humidity and temperature). Additionally, the level crossing slabs are inserted between the rails to allow the cars crossing the railway track (Fig. 8) [3].

Fig. 7. Module of the level crossing during construction

Fig. 8. Concrete level crossing slabs

It is very important to keep the contact resistance from rail to ground as high as possible for single-level railroad crossings. The stray currents can generate interference in the signal in telephone cables and can cause damages to signal and power supply cables of the barriers (see Table 1). Therefore, the best are track subgrade panels with high resistance to increase safety at level crossings. The question is: How to measure the resistivity of such panels? How to do it when there are no relevant regulations? Certain opportunities are given by the norm EN 13146-5: 2012 [1]. Track subgrade panel testing can be referred to testing concrete sleepers. In this test, the panel can be treated as concrete sleepers, in which the space between them was reinforced and poured with concrete, creating a kind of ballast-free surface. It is possible to examine the entire panel (e.g. on site or at the manufacturer) or only a piece (in the laboratory).

The electrical measurement system consisting of a power supply (transformer and autotransformer) can be used to test the panel resistance. The output of the transformer supplying the system should achieve (30+/-3) V RMS (50+/-15) Hz, as required by the norm PN-EN 13146-5: 2012. In addition, the measurement system should be equipped with an ammeter, voltmeter and recorder. The scheme of the measurement system is shown in Fig. 9 based on the standards given in [1]. The diagram indicates the places where the measurement electrodes should be applied for two test methods (red or black scheme in Fig. 9).

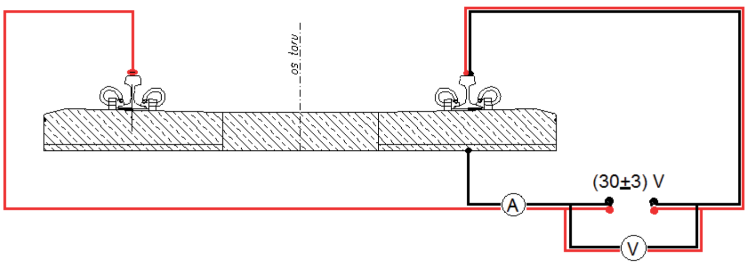

Fig. 9. System for the measurement of resistivity of the panel

In accordance with PN-EN 13146-5: 2012 [1], the measurement should be done in a ventilated room, at air temperature (15-30)°C and should last 12 minutes. The rails should be fastened to the panel under test with all the fastening elements, and the dry panel on the surface or its fragment should be placed on the insulating elements. The tested element should be sprayed with water at temperature (10-20)°C at a rate of (7±1) l/min for first 2 minutes. After sprinkling period, the observation should be continued for 10 minutes. The measurement should be repeated but the time between the measurement should not be shorter than 120 hours or until the sample dries. The second measurement taken at the longer time is valid. The contact resistance can be calculated using Ohm's law and both voltage and current waveforms recorded by the measurement system. The results should at least meet the requirements of the standard [5] or be better. Typical, resistance changes during measurement cycle based on the norm [1] is demonstrated in Fig. 10.

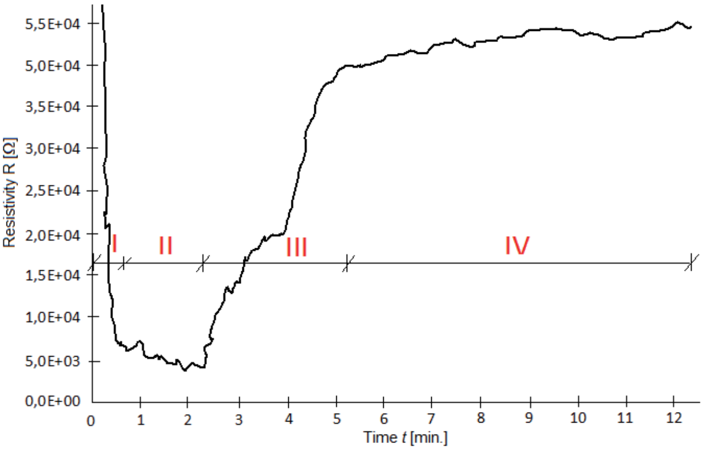

Fig. 10. Typical temporal changes in the resistivity

Four phases can be distinguished at the resistivity plot:

- Phase I – rapid decrease in resistance due to spraying,
- Phase II – resistance stabilization,
- Phase III – a sharp increase in resistance after stopping spraying the element,
- Phase IV – stabilization of resistance at a certain level.

The resistance should be similar throughout the entire railway line. If concrete sleepers are used in the track (with ballast), the resistance of the line is related to the resistance of a single sleeper. These sleepers are connected, so they should be treated as elements connected in parallel. The resistivity of the 1 km-long track in good condition is about 1 Ω [5]. Taking this into acocunt, it is important to ensure that the resistance at the level crossing does not differ significantly from the resistance of the line outside the level crossing.

4. Conclusions

We developed universal models (which are also useful in other countries) using discrete dynamical systems with oscillating properties related to the quantities such as: the number of accidents, the number of accidents at level crossings of individual categories, the number of injured people, etc.

The random character of the quantities (accidents) can be used in the analysis.

The analytical approach omit the errors that occur in numerical approaches.

In practice, it is also necessary to use Other innovative methods for activation of warning signals at level crossings, e.g. acoustic vibrations of a rail vehicle transmitted to the rails by the rolling wheels, can be used in practice.

The resistance of track subgrade panels impacts safety at level crossings.

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Bezpieczeństwo na przejazdach kolejowo - drogowych, a wizja zero

Słowa kluczowe*: bezpieczeństwo, przejazdy kolejowo - drogowe, nieklasyczny rachunek operatorów, rezystancyjność*

Streszczenie: W pracy analizowane jest bezpieczeństwo na jednopoziomowych skrzyżowaniach linii kolejowej z drogą, także z punktu widzenia znaczenia rezystancyjności płyt podtorowych.

Prowadzona analiza dotyczy bezpieczeństwa i generalnie nie odnosi się do oceny obecnie obwiązujących przepisów. W procesie badania bezpieczeństwa. pomocne jest zaawansowane modelowanie matematyczne. Do modelowania zostaną wykorzystane szczególne przypadki uogólnionych układów dynamicznych poprzez wprowadzenie do ich modelu operacji S=Δ,S=P określonych na przestrzeni C(N) ciągów rzeczywistych. W modelu tym kluczowe znaczenie mają uogólnione dyskretne funkcje wykładnicze i trygonometryczne oddające oscylacyjny charakter analizowanych wielkości. Stworzono uniwersalne modele (także przydatne do wykorzystania w innych krajach), wykorzystujące dyskretne układy dynamiczne o oscylacyjnych właściwościach w odniesieniu do liczby wypadków, do liczby wypadków z podziałem na ich udział na przejazdach kolejowych poszczególnych kategorii do liczby poszkodowanych itp. W analizie problemów może też być wykorzystywany ich losowy charakter.

Zaletą prowadzonych analiz jest uniknięcie błędów numerycznych. Wskaźnik NRV forsowany przez UE jest co najmniej dyskusyjny.

W praktyce należy też wykorzystywać innowacyjne metody, w których np. jako źródło do uruchomienia sygnałów ostrzegawczych na przejazdach kolejowych mogą być stosowane drgania akustyczne pojazdu szynowego przekazywane do szyn przez toczące się koła pojazdu szynowego.

Pokazano też znaczenie rezystancyjności płyt podtorowych dla bezpieczeństwa na przejazdach kolejowo – drogowych.

Szyny układane na płytach podtorowych nie mogą być w praktyce całkowicie izolowane od ziemi. Pewna więc część prądu trakcyjnego, płynącego przez szyny, może odgałęziać się do ziemi, tworząc tzw. prądy błądzące. Wartość oporności przejścia z szyn do ziemi zależna jest od sposobu budowy i konstrukcji nawierzchni kolejowej (np. nawierzchnia bezpodsypkowa), rodzaju podtorza i warunków atmosferycznych (wilgoć i temperatura).

Oczywiście w celu umożliwienia przejazdów przez tory pojazdom drogowym, na ogół między szyny i nie tylko układane są płyty przejazdowe. Bardzo ważne jest zachowanie możliwie dużej oporności przejścia z szyn do ziemi w przypadku jednopoziomowych przejazdów kolejowych. Wspomniane prądy błądzące wywołują np. zakłócenia odbioru w kablach telefonicznych, powodują uszkodzenia kabli sygnalizacyjnych lub zasilających napęd rogatek. W związku z tym najlepsze są przejazdowe płyty podtorowe o dużej rezystancyjności, bowiem one podwyższają bezpieczeństwo na przejazdach kolejowych. Skoro tak, to należy badać rezystancyjność takich płyt.

Pomiar zgodnie z normą PN-EN 13146-5:2012 [7] powinien trwać 12 min. i być przeprowadzony w pomieszczeniu wentylowanym, w temperaturze powietrza (15–30)°C. Przytwierdzenie szyn (szyny) do płyty powinno zawierać wszystkie elementy przytwierdzenia, a sucha płyta na powierzchni lub jej fragment należy oprzeć na elementach izolujących. Badany element należy spryskiwać wodą o temperaturze (10 – 20)°C z prędkością (7 ± 1)l/min przez początkowe 2 min. Po zakończeniu zraszania obserwację należy prowadzić jeszcze przez 10 min. Zgodnie z zasadami statystyki pomiar należy powtórzyć, jednak należy odczekać co najmniej 120 godzin lub do czasu wyschnięcia próbki i przyjąć ten czas, który jest dłuższy.

Korzystając z prawa Ohma i zarejestrowanych przebiegów napięcia i prądu w układzie pomiarowym można wyznaczyć rezystancję przejścia. Uzyskane wyniki pomiarowe powinny być co najmniej takie jak przewiduję norma [8] lub od nich korzystniejsze.

Na wykresie rezystancyjności można wyróżnić cztery fazy:

- Faza I – gwałtowne zmniejszanie się rezystancyjności w wyniku zraszania elementu,
- Faza II – pewne ustabilizowanie się rezystancyjności,
- Faza III – gwałtowny wzrost rezystancyjności po zaprzestaniu zraszania elementu,
- Faza IV – ustabilizowanie się rezystancyjności na określonym poziomie.

Na całej danej linii kolejowej rezystancyjność powinna być podobna. Jeżeli na szlaku są podkłady betonowe (nawierzchnia podsypkowa), to jej rezystancyjność powiązana jest z rezystancyjnością pojedynczego podkładu. Te pojedyncze podkłady są połączone, więc należy traktować je jako rezystancje połączone równolegle. Rezystancyjność 1 km toru w dobrym stanie wynosi około 1 Ω [8].

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