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MEASURING THE VARIABILITY OF THE PEDESTRIAN CROSSING FUNCTION IN THE SOCIO-TECHNICAL SYSTEM OF URBAN ROAD TRANSPORT

Summary. In some areas of transportation systems, reduction of risk using typical safety engineering tools can be difficult due to the relatively small number of events that can be analysed to draw conclusions for the future. One way out of this situation is to analyse systems in their normal operation when no adverse event occurs. It can be done, inter alia, with the Functional Resonance Analysis Method. An important research problem in this context is how to describe the variability of system functions. In this article, we propose an original method, based on the number of hazard sources present in a given analysis domain and apply it to a real pedestrian crossing. The obtained results indicate that the quantitative coincidence measures proposed by us are a convenient way to capture 'functional vibrations' in real socio-technical systems. This allows the prediction of undesired states of such systems based on their normal operation.

Keywords: pedestrian crossing, hazard sources, public urban transport, Functional Resonance Analysis Method

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1. INTRODUCTION

Intuitively, the traditional three-colour traffic lights remain the best form of crossing protection that practically eliminates the possibility of activating hazards. A similar phenomenon can be seen concerning railway level crossings equipped with barriers [11], although in both cases – despite advanced safety systems – there are still many hazard sources left. One of the most important of these sources was indicated by Krukowicz et al. [10]. Road traffic observations conducted by them in a large city in Poland made it possible to formulate an observation indicating that despite the improvement of traffic organisation and modernisation of traffic lights at intersections, a large number of road accidents and collisions are caused by inappropriate, often illegal behaviour of road users. A detailed literature review on the assessment of pedestrian-vehicle interaction on urban roads has been presented by Thakur and Biswas [19].

Problems in raising an already high level of safety are noticeable in many areas of human activity, including in rail transport [2, 14]. This is an example of a controller paradox [21], quoted in [4]), whose task is to minimise system variability; however, this variability is also the only way to measure the effectiveness of this controller. In such situations, it is now proposed to abandon the use of traditional methods of safety engineering (FTA, FMEA) for the benefit of new ones, allowing a comprehensive description of the system during its operation – both when everything goes fine as well as in the event of hazard activation.

Examples of new methods include the Systems-Theoretic Accident Model and Processes (STAMP), proposed by Leveson [12] and used among others for modelling maritime [8] or railway transport systems [20], where, however, its theoretical character was pointed out. STAMP is also used as an enhancement of the Event Analysis of Systemic Teamwork (EAST) method [16], which was used independently, among others, in studying the behaviour of road traffic participants during crossing intersections [15].

Another popular method of the 'new approach' (often referred to as 'Safety-II') is the Functional Resonance Analysis Method (FRAM) proposed by Hollnagel [5], and still being developed [4]. The use of the FRAM method is shown in the example of air [18] or maritime transport [13]. However, there are no applications in urban transport [17]. Furthermore, the existing publications focus primarily on modelling using characteristic hexagons rather than on the attempts to define how 'functional vibrations' manifest themselves in real socio-technical systems.

This article aims to propose an original understanding of functional vibrations for the pedestrian crossing function, as well as to determine their waveform based on our observation of a selected real pedestrian crossing in Poznan (Poland). Section 2 presents the necessary theoretical information on functional vibrations and functional resonance, as well as the applied research methodology for determining the pedestrian crossing function vibrations. While section 3 discusses the results of the observation study and shows how to apply these results for determining functional vibrations. Finally, section 4 contains conclusions and directions for further research.

2. MATERIALS AND METHODS

2.1. Functional vibrations

The concept of functional vibration is a key element of the Functional Resonance Analysis Method (FRAM) used for modelling socio-technical systems [5]. An important and sometimes overlooked aspect of the theory behind FRAM is the mere phenomenon of functional resonance, explaining the mechanism of activating hazards. According to this theory, adverse events occur not as a result of breaking (intentional or accidental) applicable procedures and specifications of the system operation but as a result of the unfavourable superposition of the functions performed in it. This is well illustrated by the diagram shown in Figure 1.

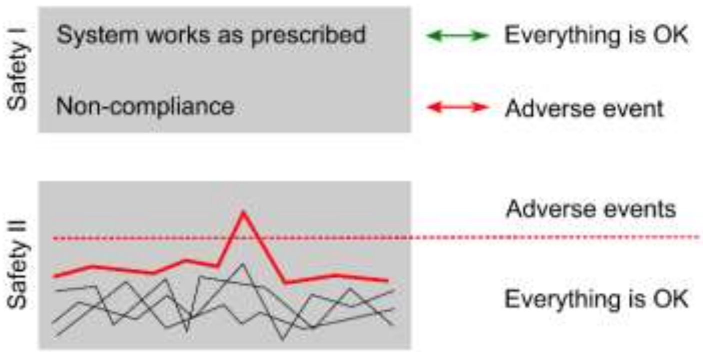

Fig. 1. Mechanism of hazard activation according to the functional resonance theory [17], based on [6]

In the theory of functional resonance (Figure 1), it is assumed that the result of the system's operation is the composition (superposition) of its functions. The superposition is variable over time but usually remains below a certain limit, which exceeding results in the activation of a hazard (an adverse event, an accident). Such a view on the work of socio-technical systems allows them to be improved also when there are no adverse events. Thus, one should examine the various ways of correct system operation – the variability, as Hollnagel calls it – and undertake actions aimed at limiting this variability.

In this study, we suggest that variability is described using the hazard sources that appear during the implementation of a given function. A hazard source (also called 'a risk source') is an element, which alone or in combination with other elements, has the potential to give rise to (typically) undesirable consequences [1, 7]. A broader discussion on the motivation to choose such a definition was presented in [3]. The most important is that two or more hazard sources may not be harmful; however, when combined they interact to become dangerous [9]. This is graphically depicted in Figure 2.

We, therefore, propose that variability V of the function performed by the socio-technical system in time would depend on the number of occurrences of hazard sources identified in the analyses domain in subsequent observation time intervals of this domain, that is:

$$V = f\left(q_{HS_i}^{k}\left(\Delta t_{j-1,j}\right)\right),\ i = 1,2,\ldots,n,\ j = 1,2,\ldots m,\ k = 1,2,\ldots l \tag{1}$$

where V is the value of variability determined in the observation time interval $\Delta t_{j-1,j}$ and $q^k_{HS_i}(\Delta t_{j-1,j})$ denotes the number of occurrences of the i-th hazard source from the n sources identified in a given analysis domain in the j-th observation time interval. Because the data can be registered in several measuring sessions (for example, different days of the week) covering the same observation time interval $\Delta t_{j-1,j}$, a counter k was introduced to denote observation time intervals occurring at the same clock time in several measuring sessions.

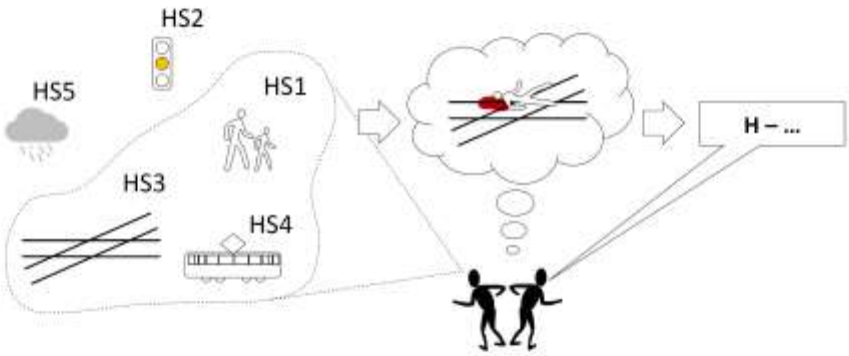

Fig. 2. Schematic representation of the relation between the hazard source (HS) and the hazard (H), as considered in this study

Describing variability using Equation (1) allows differentiating between two levels of superposition. First, there can be many hazard sources occurring during the performing of one function of a socio-technical system, and their number is variable over time. The variability of a particular function will therefore be given by the superposition of the number of occurrences of individual hazard sources. Second, in the context of performing all functions by a socio-technical system, the superposition concerns variations coming from all its functions – and this superposition, following the FRAM assumptions, determines the possibility of having an adverse event.

2.2. Selection of case study crossing

To carry out the variation measurement, we have selected a pedestrian crossing equipped with traffic lights located near two significant pedestrian traffic generators (Figure 3). The first of them is the campus of the Poznan University of Technology, used by approx. 20,000 students. In the immediate vicinity of the crossing, both the most important didactic buildings and dormitories are located. The second generator is Posnania, one of the largest shopping centres in Poland. In addition, near the pedestrian crossing, there is an intersection of two tram routes. This makes the tram stop located at the crossing to be often used by passengers who make transfers.

The crossing leads through two roadways and two tram tracks between them. The street is a fragment of the second communication frame, that is, the bypass of the city centre. The western roadway has two lanes, the eastern – four lanes, including one for turning into the shopping centre. The maximum valid speed for all roadways is 50 km/h. Three sets of traffic lights are installed at all parts of the crossing: two on the roadway crossing, and one on the tram track crossing. The condition of the roadway surface and tracks were assessed as good, not interfering in any way with the movement of vehicles. Visibility is very good, as there are no buildings or advertisements near the crossing that could limit it. Within the crossing, there is street and tram stop lighting that is sufficient to light the roadways as well.

To facilitate the collection of observational data at the pedestrian crossing, it was divided into two zones (Figure 4). Zone I includes the crossing through the tram track and the adjacent tram stop Kórnicka. While Zone II covers the rest of the pedestrian crossing, that is, the roadways in both directions.

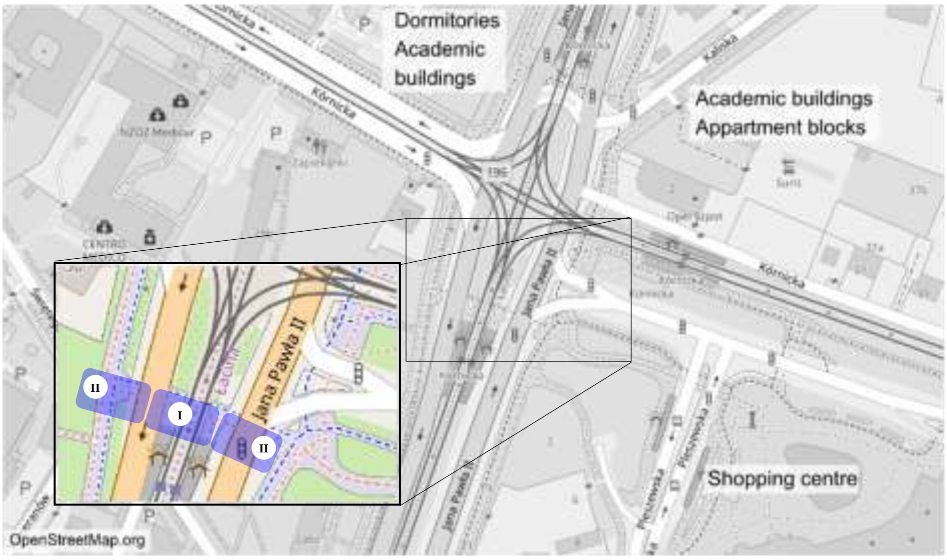

Fig. 3. Location of the case study crossing and indication of its zones

Due to the lack of possibility to observe the entire tram stop, Zone I (Figure 3) only includes a part of the stop adjacent to the crossing. Due to the fence mounted along the tram stop between the tracks, people wanting to cross the tracks most probably used the monitored pedestrian crossing for this purpose.

2.3. Measurement procedure

Before commencing the main observation study, a pilot study was carried out to develop a catalogue of hazard sources appearing on the selected pedestrian crossing. The catalogue developed in this way was the basis for the preparation of the first version of the measurement card, supplemented during the main study with further hazard sources identified in its course. On the measurement card, the following were recorded:

- Date and time of measurement.
- Atmospheric conditions during measurement (for intensive snow/rain, cloudy, sunny).
- Traffic intensity of trams, cars and pedestrians (Table 1).
- The fraction of older people at the crossing (in percents).

The card also records information about the pedestrian's attitudes to identify hazard sources (for example, looking around before entering the crossing); however, due to the subjectivism of the assessment, it was not included in the subsequent development of the research results.

Tab. 1

Taxonomy of traffic intensity determined during this study

Key word	Number of trams [per 15 min]	Number of cars [per 15 min]	Number of pedestrians [per 15 min]
Small	<3	<400	<100
Medium	3-7	400-700	100-400
Big	>7	>700	>400

The basic type of traffic violation, which is also a hazard source, is the use of crossing when it is not allowed to do so. To better analyse the behaviour of pedestrians and cyclists, the observed events were assigned to the following categories of hazard sources:

- Red light: traffic jam all lanes. These are events when a pedestrian moves from the area of the tram stop between cars immobilised in all lanes.
- Red light: traffic jam one lane. In this type of event, cars were immobilised only on a lane adjacent to the area of the tram stop, and the remaining lanes were free.
- Red light: entering in front of a tram. In case of some events of this type, pedestrians took advantage of the fact that the tram was staying at the stop with its door open (passenger exchange was ongoing).
- Red light: entering in front of a car.
- Red light: other cases.
- Flashing green: pedestrian crossing.
- Red light: bike crossing.

Each event was qualified only to one of the above categories of hazard sources.

Some of the observed pedestrians did not cross the roadway/track at the red light, but they waited for the green light close enough to the edge that it was considered to be a hazard source. There are two sources of this kind distinguished here: too close to the roadway, and too close to the track. During the measurements, all cases of using the wrong part of the crossing or going through roadway/tracks outside the designated crossing were recorded. The following hazard sources were distinguished in this regard: pedestrians on the bike side, bikes on the pedestrian side, pedestrians outside the crossing, and slow motion on purpose. Situations in which pedestrians passed through the part intended for cyclists and completely left the designated crossing were not counted as the hazard source ‘Pedestrians on the bike side’ but only as 'Pedestrians outside the crossing'. In addition to events that are direct violations of the current rules for the use of crossings, events that limit the situational awareness of people on the crossing were also registered and are treated here as hazard sources: using a mobile phone, using headphones, running through the crossing. It should be noted that the behaviour of one person could generate several hazard sources, for example, in a situation when a pedestrian with headphones is running through the crossing.

3. RESULTS

3.1. Empirical results

This research was carried out in two periods: autumn-winter and spring. Data registration took place in 6.5-hour measuring sessions, carried out between 10:00 and 16:30 on selected days of the week. The hours included the evening communication peak. Measuring sessions were divided into fifteen-minute time intervals. The research was planned in such a way that the data registration took place at least once in each observation time interval.

A summary of the results of this study carried out in the autumn-winter and spring periods is shown in Table 2. In the case of hazard sources for which it could have been significant, the zone of occurrence of the hazard source was also registered (following Figure 3). This has an impact on the number of occurrences of hazard sources because the behaviour of one pedestrian crossing in the wrong way was recorded three times: once in Zone I (crossing the track) and twice in Zone II (crossing the eastern and western roadway).

Sources of the hazard that generates the largest losses – that is, 'Possibility of incurring losses/damage because of a pedestrian being hit by a car or tram' – is the presence of a pedestrian at the crossing in a situation where the red light is on. Based on the observation results (Table 2), it can be stated that this is a relatively frequent situation. For example, in the spring period, 653 cases of the occurrence of this hazard source were recorded on the entire crossing followed by 402 more situations of entry onto the roadway or the track at a flashing green light. However, it was also possible to observe various pedestrian motivations for such behaviour (Figure 4).

Tab. 2

Observed number of hazard source occurrences in the autumn-winter and spring measurement sessions

No.	Hazard source	Zone	Number of occurrences	
			Autumn-winter	Spring
1	Red light: traffic jam all lanes	II	7	27
2	Red light: traffic jam one lane	II	21	27
3	Red light: entering in front of a tram	I	60	46
4	Red light: entering in front of a car	II	24	35
5	Red light: other cases	I	276	239
		II	230	220
6	Flashing green: pedestrian crossing	I	211	199
		II	200	203
7	Red light: bike crossing	I / II	16	59
8	Too close to the roadway	II	79	80
9	Too close to the track	I	132	136
10	Pedestrians on the bike side	I	125	137
		II	183	188
11	Bikes on the pedestrian side	I	111	147
		II	81	110
12	Pedestrians outside the crossing	II	554	593
13	Using mobile phone	I	100	104
		II	138	135
14	Using headphones	I	111	122
		II	146	146
15	Running through crossing	I	75	81
		II	101	111
18	Slow motion on purpose	I	99	88
		II	120	113

The data presented in Figure 4 indicate a relatively small proportion of situations in which pedestrians would enter directly before an oncoming vehicle – a tram or a car. The share of this type of hazard source in the group of all sources related to the crossing on a red light is within 5-10%, depending on the season and part of the analysed crossing. The percentage share is higher in the case of crossing the tram tracks; however, it should be noted that entering in front of a tram also means the situation in which the pedestrian passes in front of the tram in which the exchange of passengers is ongoing. If there are no other sources, such as the fall of a pedestrian who lying on the ground is not in the driver's view, the activation of the hazard is relatively unlikely.

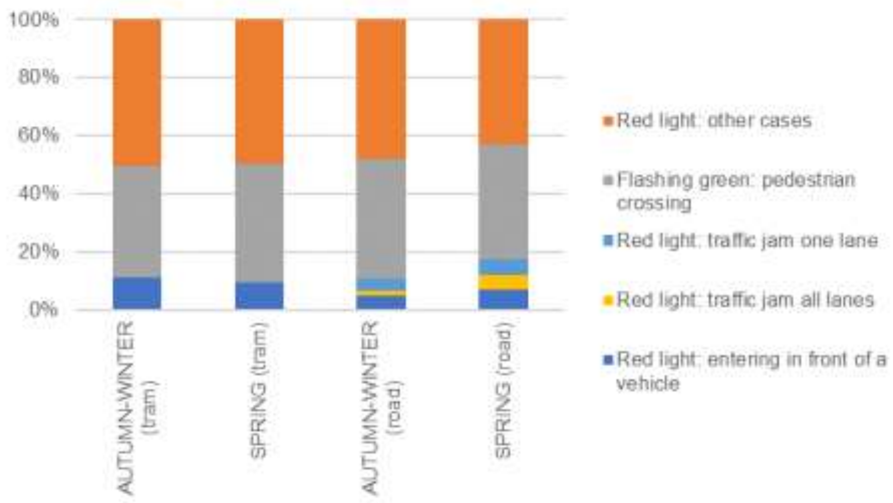

Fig. 4. Share of different types of red-light crossing, distinguished during this study

During the tests, it was also noticed that pedestrians were confused over the light signals and intended to pass through the track and across the roadways, thus starting to cross the road when the green light in the signalling device for tram tracks was lit. There were also situations in which pedestrians entered the crossing between cars standing in a traffic jam, which – just like in the case of trams with open doors – can lead to losses only when other, rarely occurring hazard sources are present at the same time.

3.2. Variability function

Number of occurrences of the i-th hazard source in the j-th observation time interval $\Delta t_{j-1,j}$ is a random variable. In addition, these numbers in subsequent measurement sessions form a finite set Q of random variables $q_{HS_i}^{k}(\Delta t_{j-1,j})$, that is:

$$Q = \{q_{HS_i}^{k}(\Delta t_{j-1,j})\} \text{ for } k = 1,2,\dots,l. \tag{2}$$

From the standpoint of the superposition of occurrences of individual hazard sources, the most important is the maximum value that can be taken by a random variable $q_{HS_i}^{k}(\Delta t_{j-1,j})$. For the purpose of presenting the results of empirical studies, it was assumed that the number of occurrences of the i-th hazard source $q_{HS_i}(\Delta t_{j-1,j})$ in the j-th observation time interval is equal to the maximum number of occurrences of this source observed in the interval $\Delta t_{j-1,j}$ in subsequent measurement sessions:

$$q_{\mathrm{HS}_i}(\Delta t_{j-1,j}) = \max_k Q \tag{3}$$

In the theory of functional resonance, it is assumed that the result of the system's operation is the composition (superposition) of its functions. The presented examples allows determining the form of the function *f* (Eq. (1)) given by the following formula:

$$f\left(q_{HS_i}^k(\Delta t_{j-1,j})\right) = \sum_{i=1}^n q_{HS_i}(\Delta t_{j-1,j}). \tag{4}$$

Given the assumptions made previously (Eq. (3)) and dependencies (1) and (4), the variability over time $V(t_j)$ of a function performed by a socio-technical system can be expressed as follows:

$$V(t_j) = \sum_{i=1}^n \max_k \left(q_{HS_i}^k(\Delta t_{j-1,j})\right). \tag{5}$$

The method of determining the value of function variation $V(t_j)$ for one observation time interval covered by three measurement sessions (days) is shown in Figure 5.

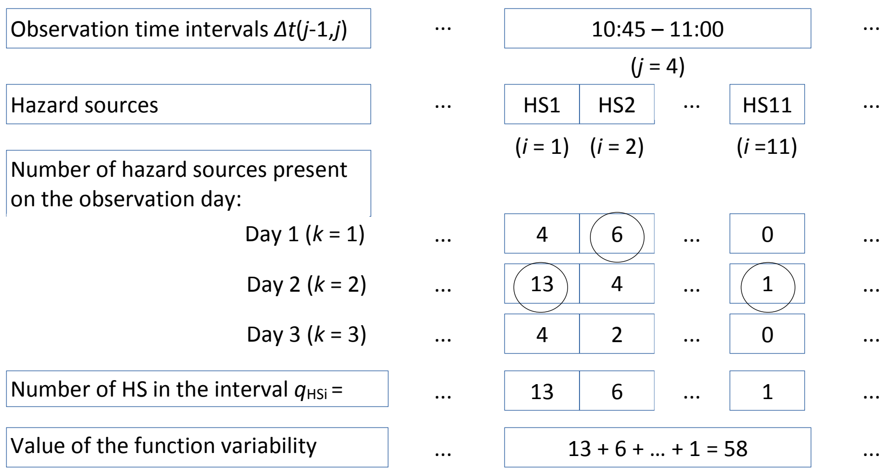

Fig. 5. Method of determination of the value of variability of a socio-technical system functions (pedestrian crossings) for one observation time interval covered by three measurement sessions (days)

Performed empirical studies describe the state of the pedestrian crossing during the day (from 10:00 to 16:30), that is, the number of hazard sources occurring in individual observation time intervals (according to Equation (1)). To determine the waveform of variability of the pedestrian crossing function, it is necessary to assign the identified sources to a specific zone, according to the information contained in Table 2, column 3.

The recorded number of individual hazard sources allows to draw a waveform of variability of the crossing function through the considered part of the crossing according to the dependence (4). Figure 6 shows the waveform of variability as the sum of all occurrence numbers of hazard sources in each observation time interval.

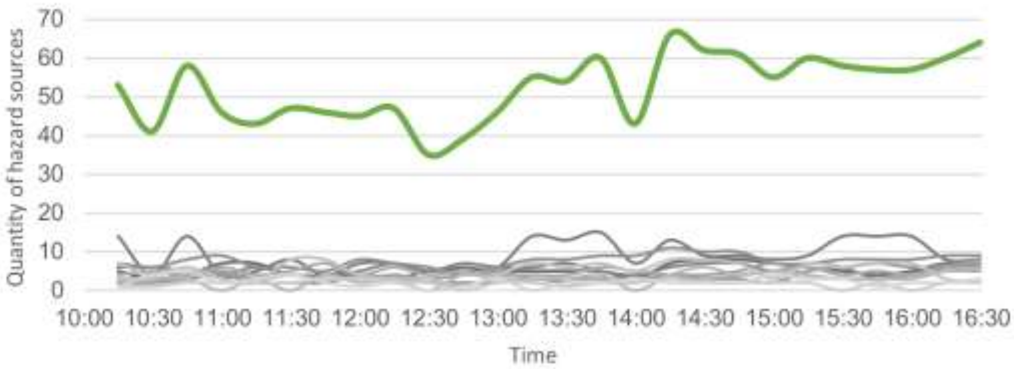

Fig. 6. Superposition of hazard source quantities at the tram part of the crossing in spring

4. CONCLUSIONS

The concept of functional resonance is so mature that now it is worth taking action at the stage of its application. There is a lack of such activities in urban rail transport, and the existing ones (in other domains) do not give a precise answer on how to understand ‘functional vibrations’ in real socio-technical systems. In our opinion, the problem consists in the lack of adequate models and quantitative measures describing functional resonance. For this reason, we proposed a proper understanding of functional vibrations for the pedestrian crossing function. We also showed how to determine the variability values of this function based on our observation study of the selected real pedestrian crossing.

We, therefore, propose that variability of the function performed by the socio-technical system in time would depend on the number of occurrences of hazard sources identified in the analysis domain in subsequent observation time intervals. As part of the work on how to describe the variability of the system's functions, we also considered other possibilities for its implementation. First, we considered the fact that adverse events are usually caused by the coincidence of hazard sources and not the activity of a single source. In such a case, an interesting group of models and measures of variability of the system's functions may be the measures of diversity.

Implementation of the description of the system's functions variability using the presented models and measures is a relatively simple task. However, the interpretation of the mathematical dependences used for this may be troublesome. With this in mind, we have prepared appropriate diagrams showing how to determine the value of variability of the socio-technical system function (pedestrian crossing) in practical applications.

To develop the models proposed by us and measure the variability of a system function, we planned and performed appropriate observations. On this basis, we have shown that the quantitative coincidence measures proposed by us are a convenient way to capture ‘functional vibrations’ in real socio-technical systems.

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