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Improvement of Railway Signalling System by Using Cyber-Physical Model

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Abstract: The railway signalling system is the basic railway traffic management system. Constant changes in technology and traffic safety requirements have resulted in numerous solutions applied to date. The complexity of the railway management system dictates changes. However, the importance, volume and security of the railway management systems caused a rather slow adjustment to new technologies. Today, the main pillars of the development of new advanced systems are the Internet of Things, cloud computing, artificial intelligence, data analysis, Industry 4.0 and cyber-physical systems. Therefore, this paper will present the development of a cyber-physical model of the signalling system of a single-track railway. Observing the railway signalling system as a unique cyber-physical model enables the introduction of layered development and infrastructure upgrade. Such a comprehensive approach represents a kind of a turnaround in industrial development and planning, which results in more lasting solutions in the fields of traffic safety, efficiency and maintenance.

Keywords: cyber-physical system; Industry 4.0; railway; signalling system; traffic safety

1 INTRODUCTION

The main motives for creating a cyber-physical model of the railway are the features and capabilities of platforms based on modern information and communication technologies (the Internet of Things, large data sets, cloud computing, data analysis, etc.). Cyber-Physical Systems (CPS) is the integration of computing, communication and storage capabilities with monitoring and controlling the entities in the physical world [1]. Through Industry 4.0 standards and with the support of modern broadband communication networks [2, 3], these technologies provide a new view on rail transport systems, eliminating existing limitations in terms of data size, baud rate and system reliability. The aim of this paper is to present the methodology for the development of a cyber-physical model of the railway signalling system that is applicable to existing railway lines. The development of such model proves that it is possible to open investments in the field of signalling, traffic safety and communication equipment without major construction works on railways, which would result in a significant increase in traffic safety, modern train management, faster traffic and efficient and fast system maintenance [4]. Also, numerous opportunities are opened for the implementation of new solutions, approaches and systems in railways, such as communication of the management system with all traffic participants, securing of the less frequent road crossings, machine-machine communication interfaces and the like.

The paper is structured as follows. Section 2 gives the concept of a cyber-physical model of the railway signalling system in layers, as well as the technological segments contained in individual layers. Section 3 describes the characteristics and provides a division of data collected in the physical layer. Section 4 defines the protocol used to exchange data within the model. Section 5 presents the basic settings of the model as well as the limitations in terms of space and time that are a prerequisite for work simulation. In this part, a universal approach to the development of cyber-physical railway model is presented. Section 5 also gives a description of the performance of the visualization of the model operation simulation procedure, which is the basis for the development of system user interfaces. Section 6 presents an analysis of the results and improvements achieved by the introduction of a cyber-physical access to real railway signalling systems. The analysis was performed from the point of view of the impact on both the traffic safety segment and the system maintenance segment. Concluding remarks and future work are presented at the end of the paper.

2 DEVELOPMENT OF A CYBER-PHYSICAL MODEL OF THE RAILWAY SIGNALLING SYSTEM

The cyber-physical model of the railway signalling system represents a new global view of all its associated systems and elements. The layered representation of the model is presented in Fig. 1, which shows three layers of the railway signalling system, i.e. physical, transmission and cybernetic.

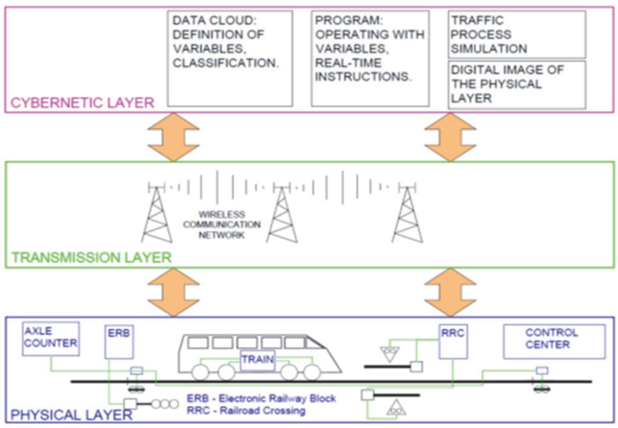

Figure 1 Layers of the cyber-physical model of the railway signalling system

In what follows, the layers shown in Fig. 1 are described by three steps of building a cyber-physical model. Based on experience of real systems [5] and due to the need for functional integration of different local subsystems into a single model, the first step is to upgrade elementary signalling subsystems (power units, signals, switches, central control of sections, railroad crossings, trains) [6, 7]. Such approach will first improve the functionality and reliability at the field equipment, and then enable the construction of a physical layer of the model that should change the current principles of rail traffic in terms of centralized data collection and processing. The second step is to create a highly reliable communication network with a high level of reliability, because, as a transmission layer, it represents the backbone of the model's operation. The transmission level relies on modern principles of wireless communication networks based on the 5G standard [8], with no restrictions on the use of wireless networks based on some other conceptually similar network standards. The new generation of communication networks must enable very high transmission speeds and a significant increase in bandwidth in order to achieve reliable signal transmissions [9]. Another important feature of new networks is the provision of uninterrupted connection of devices at any location and for any concentration of devices [10]. The third step is to create a cybernetic layer consisting of appropriate computing resources and software solutions. The cybernetic layer enables reliable and accurate processing of input data in real time so that all elements of the system and users have access to the correct output data according to which the correct actions are taken in the system processes [11]. Therefore, it is extremely important to create quality IT solutions through which improvements in the physical, communication and transmission layer will be used in the best possible way. Only with quality design and construction of all three layers (physical, portable, cybernetic), it is possible to view the signalling system of the railway as a unique cyber-physical model. The cybernetic layer will be observed through a higher level of functioning using cloud computing technology [12]. Cloud computing technologies enable decentralized storage of data collected from devices in the field [13]. Further, the stored data is ubiquitous, which means that it is possible to access data from any device from the field at any place and at any time. For example, the driver is given access to data from all devices on the railway as well as all other system data that could help in decision-making. This is a revolutionary improvement from the aspect of train management as so far the driver has had limited information about the system in motion and a lot has depended on his/her perception and memory. The cyber-physical model can transfer a complete digital image of a track and a train to a locomotive and register real-time alarms (road crossing states, signal states, train states) that will enable preventive actions in management to avoid accidents. In the case of a signal failure on the track in front of the train or a train failure, the driver would be notified immediately, so that he/she could quickly adapt the ride to a new situation.

The cyber-physical view of the railway signalling infrastructure enables the creation of hardware independence for the system elements and the use of universal hardware solutions. This is a significant change compared to previous systems because of greater system flexibility. Also, the equipment becomes cloud-enabled, which allows more comprehensive integration of elements, reduction of existing complex systems and centralization towards a single control Centre. Siemens Mobility and ÖBB-Infrastruktur AG in November 2020 had put first hardware independent cloud-enabled station interlocking in operation. This project presents the first-ever approval of a SIL4 (Safety Integrity Level 4 – Based on IEC 61508 standard) interlocking on a COTS (Commercial Off The Shelf) hardware and is therefore an international pilot and reference project. Main advantages of this implementation are better cost efficiency and flexible maintenance. In addition, system contributes to sustainability, by providing savings in terms of space and energy, compared to existing systems [14]. According to the same approach implemented in the mentioned project for one railway station, in this paper is presented a cyber-physical model for the wider railway signalling infrastructure. Same approach is recognized in terms of cloud-enabling signalling equipment and creation of unique, upgradeable centralized software. The successful implementation of the project for one station and reaching the SIL 4 security level of the system is an argument more for the feasibility of transforming the signalling system of the wider railway network into a unique cyber-physical system.

The three-layer cyber-physical model of the railway signalling system shows necessary stages of model development, starting with equipment interventions in the physical layer, then transmission infrastructure and the structure of the cybernetic layer to process the collected data. Prior to data processing, data distribution should necessarily take place, what is presented in Chapter 3.

3 DATA DISTRIBUTION IN THE CYBERNETIC LAYER OF THE RAILWAY SIGNALLING SYSTEM MODEL

Each device in the signalling system, previously shown by the physical layer of the railway signalling system in Fig. 1, generates a series of data used to control certain processes. Thus, for example, advanced electronic railway blocks, as wireless communication devices, are used to control the signalling of track section occupancy [15, 16]. ERB is a device with a built-in microprocessor that integrates equipment functions for a specific section of track. These are the signal functions for both directions of movement and the functions of the axle counters to control the section occupancy. The device has also been upgraded with power supply device control. Through a series of defined communication interfaces, this information can be stored on a server and with the help of this information; other participants can be informed about the occupancy of that section based on a programmed interface that is also located on that server. All stored data must form a coherent structure to facilitate access and manipulation. The principle of data storage in such system can be explained by means of a data cloud [17]. Namely, each data cloud represents a set of programmable interfaces, relational databases in which all data related to that cloud are located, and a set of interfaces through which other rail participants are informed. The data generated by the upgraded devices can be classified according to different mission-critical processes in the railway to which they belong (data for railway traffic from the immobile equipment, data from train equipment, data for equipment operating correctness). The distribution of data in the model was performed as three domains of data clouds based on which the railway data model was built, as shown in Fig. 2. Data important for the condition of the equipment in the field is stored in a data cloud called "Equipment in the field correctness". Furthermore, data related to the current equipment status in the field is stored in the "Field equipment states" data cloud. The third cloud is called "Train equipment states" and it stores all data important to the assemblies and devices on the train. Data clouds are formed from state variables of elements in the field, which are structured as binary data.

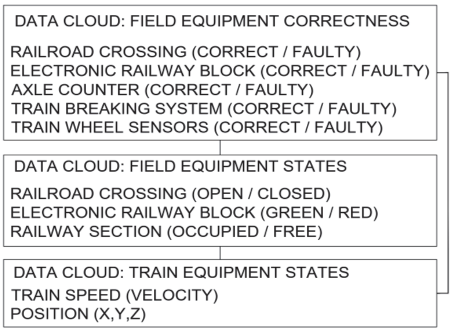

Figure 2 Railway signalling model data distribution in three domains

This data distribution in three domains has created a precondition for defining the protocol through which data will be exchanged. The principles on which the protocols are based are described in Chapter 4.

4 COMMUNICATION PROTOCOL FOR DATA EXCHANGE BETWEEN SERVERS AND DEVICES IN THE PHYSICAL LAYER OF THE MODEL

For software realization of the aforementioned architecture, a communication protocol has been implemented based on which the data is distributed in a precisely defined data cloud. Also, on the basis of a defined protocol, access is made to data already stored on the server. The protocol for data exchange in the program is modelled on the HTTP protocol and it contains two essential methods [18]. The first method based on the HTTP GET method is used to retrieve data stored on the server. A generic example of requesting data from a server is: GET:DATA_CLOUD_NAME: DEVICE_NAME: VARIABLE_NAME;

The server must respond to the request in case of both a successful data request and an unsuccessful data request (a variable or device does not exist or the method is not well defined). The answer must therefore contain the query status and the value of the requested variable. A generic example of a response to a GET request is as follows: STATUS:TIME_OF_THE_LAST_VARIABLE_VALUE _CHANGE: VARIABLE_VALUE;

The second method used for data storage is defined by the HTTP POST method.

Similarly to the GET method, the client sends a single-line message as follows: POST:DATA_CLOUD_NAME:DEVICE_NAME:VARIABLE_NAME:ENROLLMENT_TIME:VARIABLE_VALUE;

A server response to this request indicates successful or unsuccessful data storage (OK or FAIL).

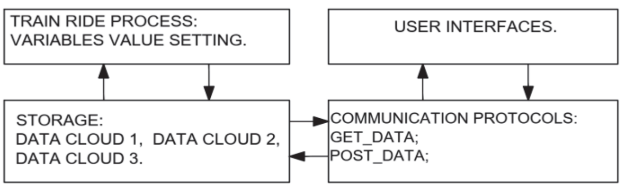

Figure 3 Software architecture

The software architecture of the model is shown in Fig. 3. In the first block, the time process of train ride is running, according to which the values of the variables are assigned. This process reads and stores variable data according to the main algorithm Fig. 4. Communication protocols allow the acquisition and storage of data via user interfaces at the same time.

In this chapter, a basic tool is created by defining methods for taking and storing data, through which the program will function in the cybernetic layer of the model, Fig. 1. The next chapter presents model simulation, where spatial and temporal constraints for real parameters will be defined to form the created physical layer in the cybernetic layer.

5 SIMULATION OF THE OPERATION OF THE RAILWAY SIGNALLING SYSTEM MODEL

In earlier chapters, equipment in the physical layer was modified to obtain data that could describe well the operation of signalling equipment on the railway. This data is then classified and prepared for program processing. In order to build and show the actual operation of signalling equipment on the railway, the performance of the simulation of the train running on the assumed railway line section will be described below. The simulation is based on the described distribution of data in three domains, the use of developed data exchange protocols and the introduction of certain spatial and temporal constraints as necessary assumptions for elements that make the model generally applicable and would otherwise be clearly defined for any real railway example. Spatial settings of the model are based on a single interstation distance divided into six controlled sections.

The simulation of railway traffic in the time domain was performed as a continuous process. Every second the process scans the current time and based on this input parameter and the daily timetable, active train running status is defined and the current position of the train is determined. The section where the train is located is determined based on the defined position of the running train, and after that, the values of variables related to the state of certain elements of the signalling system are set. A level crossing was set up on the fifth controlled section. Cyclic states of model variables are stored in internal files. Their states can be changed from the outside as well. Diagram in Fig. 4 represents the algorithm of the internal data recording.

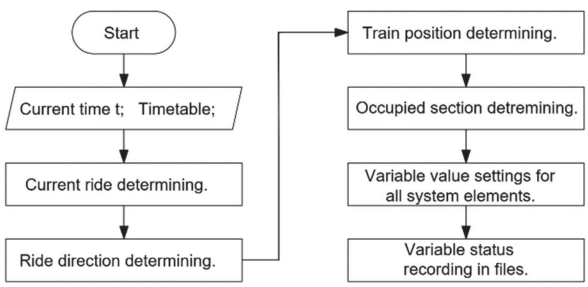

Figure 4 Internal data recording algorithm

The algorithm was implemented in the Python programming language. Json file types were used for storing the state values of the railway infrastructure elements. Such record allows writing in the form closest to the semantic structure of variables, i.e. keys associated with certain values.

A key represents the name of a particular variable to which a particular value is associated. An example of a json record is:

{PARAMETER_NAME:PARAMETER_VALUE}.

The simulation was created over two groups of files, i.e. status files and failure and disturbance files. There are four status files:

APB - automatic track block status files, there are seven of them on the selected track section;

BO - axle counter status files;

CPR_STATUS - a road crossing status file;

TRAIN - a file that determines the current state of the train.

The second group of files is formed by device failure and disturbance variables. One file has been created for each device on the model track section and it is uniquely determined by its name. Fig. 5 shows the universal approach to the development of Cyber-Physical railway models.

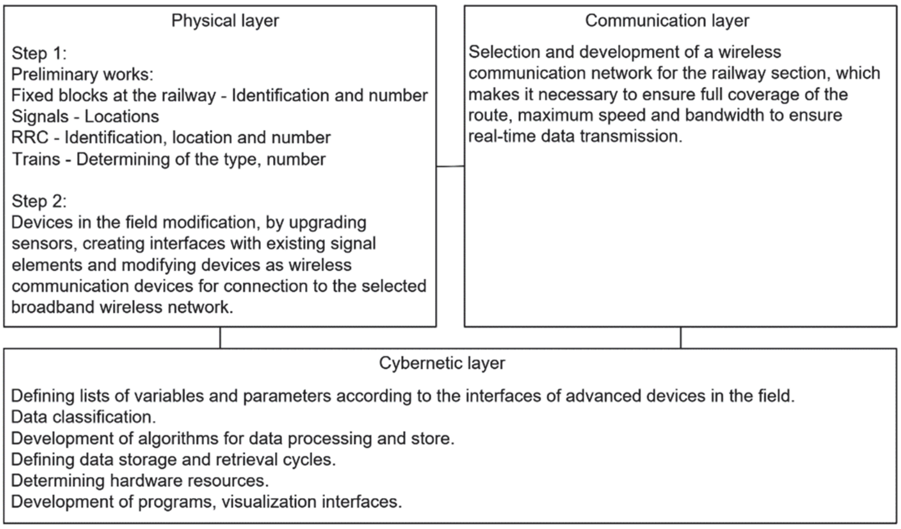

Figure 5 Universal approach to the development of Cyber-Physical railway model

The key benefit of applying the cyber physical model to the classical railway is the storage and processing of data in one center, real-time distribution of data to all elements of the system. Universal improvements achieved through its implementation are:

- Creating a real-time digital image of systems and driving processes in all key positions, thus solving the fundamental problem of classic systems - blind/inaccessible elements
- Increased possibility of automatic actions in the process.
- More accurate and faster detection of current faults.
- Possibility of creating new databases on the state of all elements of the system through operation due to the development of quality preventive maintenance plans.

Due to a review of the state of the system and the possibility of remote action to change certain parameters in the devices, a graphical user interface of the model was created. The visualization interface is the last step to complete the cyber-physical model of the system. In order for the saved data to be graphically displayed and accessible via the Internet, the following technologies were applied: HTML, JavaScript and SVG [19, 20]. The main advantage of this approach is full real-time data transparency. This practically means that in any place where there is a need (e.g. control centre, train and maintenance service units in the field) it is possible to create the desired visual interface. This was made possible by modifications to each device in a field that now houses at least one sensor and one microcomputer. This allows each device to send information about its operating condition and correctness condition to the system. General architecture for visualization interfaces is presented in Fig. 6.

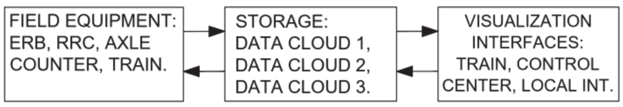

Figure 6 Visualization interfaces data exchange

Visualization interfaces are designed according to the functional affiliation of the data. They are placed in the cybernetic layer of the model and interchange with the data stored on the server. In the event of a malfunction, this information is provided to the master server from where it is available to all system users that are programmatically enabled. The occurrence of a malfunction or disturbance on the railway elements is one of the essential effects that are an integral part of the model. Each element has defined variables that indicate a specific malfunction or disturbance in the system.

6 SIMULATION RESULT ANALYSIS OF THE PROPOSED MODEL OF THE RAILWAY SIGNALLING SYSTEM

The selected railway section model is made on actual settings according to the bottom-up principle. At the lowest level, i.e. in the physical layer, by the analysis of elements and devices that are retained (power units, signals, switches, central control of sections, railroad crossings, trains), their limitations are identified in terms of their communication interfaces, so in principle upgrades and modifications in electronic circuits are made based on which new interfaces were created, which were used as the basis for making a cybernetic model. Numerous limitations (as limited number of fault signals, limited or no communication between devices in the field, unreliable real-time device status monitoring) have been removed by modifying the physical layer interface, which made an insight into the basic states and the states of device failures impossible in previous systems.

The architecture of the cybernetic model is made according to the classification of variables whose values are generated via the interface of devices modified in the field. In order to develop a railway model according to the requirements of Industry 4.0, the data cloud principle was applied to data storage and operation. Cloud computing technology enables decentralized storage of data collected from devices in the field. Likewise, accessibility from any system device is possible anywhere and at any time.

6.1 Increasing Railway Capacity

In order to show the possible contributions of a cyber-physical model on the real signalling system, the actual section of the railway in the European transport corridor Vc will be taken for analysis. Railway traffic simulation will be implemented on the section through the Republic of Croatia from Vrpolje to the state border Cro/BiH. This is a single-track line with a length of 21.89 km which contains three railway stations (Vrpolje, Kopanica and Slavonski Samac), 21 railroad crossings and 11 sections protected by ERB signals [21]. The geometrical characteristics of the railway are favourable for speeds up to 120 km/h in certain sections, but due to the large number of railroad crossings, with different levels of safety equipment the actual train speed is limited to 40 km/h in critical places, which significantly lowers the average speed on this section. The actual train speed diagram is shown by the blue line in Fig. 7, Fig. 8 and Fig. 9. With the implementation of a cyber-physical system for signalling systems on this railway section, all railroad crossings would be equipped and integrated so the train driver would have a real picture of the line section he/she encounters, which would increase speed limits to maximum possible values allowed by geometric characteristics of the line. The speed diagram would then look like the orange line in Fig. 7, Fig. 8 and Fig. 9. On RRC's in the classic signalling it is visible that the train has to slow down up to 40 km/h due to speed limit because there is no information about the state on RRC. On the same RRC with application of the cyber-physical model, the speed limits are higher up to 80 km/h because the train and the control centre have data on the correctness and free passage through the RRC, which results in increasing the speed of train. The longest section of the railway line between the two stations is relevant for the calculation of the average speed and capacity, which is here the section from the station Kopanica (8,927 km) to the station Slavonski Samac (18,992 km).

The average speeds from the speed diagrams in Fig. 5 and Fig. 6 are:

$$v_{m1} = 64,03 \text{ km/h},\ v_{m2} = 81,17 \text{ km/h} \tag{1}$$

The capacity of a single-track railway is defined as the maximum number of trains that can be dispatched from a given station, considering the time required for train run from the opposite direction, during 24 hours [5]. Railway capacity is calculated by the following expression:

$$N = \frac{1440 \text{ min}}{2 \cdot t_d \text{ min}} \tag{2}$$

t_d is the total train run time between two stations.

Distance between stations Slavonski Samac and Kopanica is calculated as a difference of kilometre positions:

$$L = 18,992 \text{ km} - 8,927 \text{ km} = 10,065 \text{ km} \tag{3}$$

The total train run time between these two stations for actual conditions is calculated as:

$$t_{d1} = \frac{L}{v_{m1}} = \frac{10,065 \text{ km}}{64,03 \text{ km}/h} \cdot 60 = 9,43 \text{ min} \tag{4}$$

The total train run time between stations for the signalling system performed according to the proposed cyber-physical model is calculated as:

$$t_{d2} = \frac{L}{v_{m2}} = \frac{10,065 \text{ km}}{81,17 \text{ km}/h} \cdot 60 = 7,44 \text{ min} \tag{5}$$

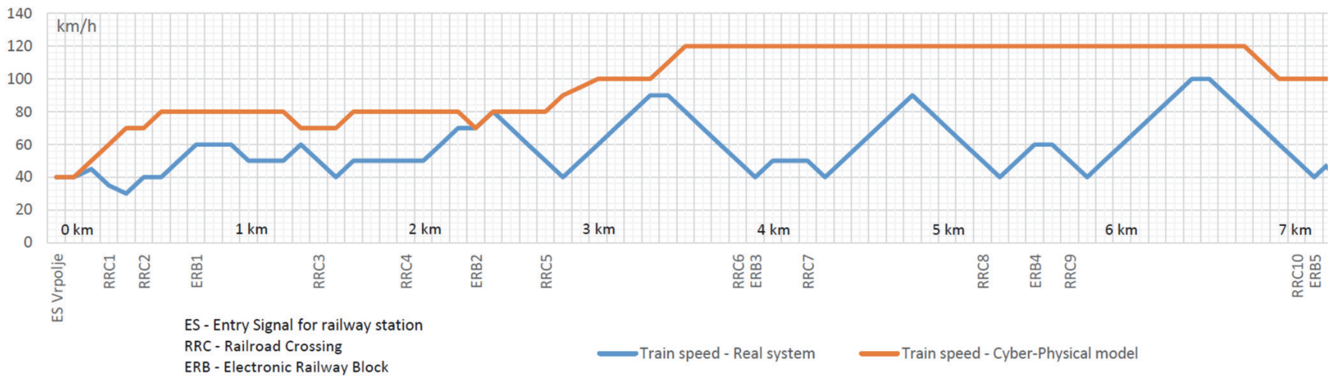

Figure 7 Train speed diagram from km 0 to km 7 on the railway: Vrpolje - State border Cro/BiH

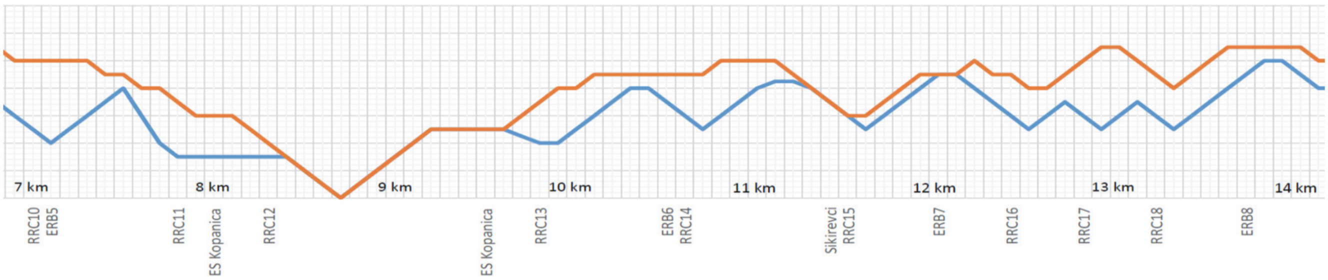

Figure 8 Train speed diagram from km 7 to km 14 on the railway: Vrpolje - State border Cro/BiH

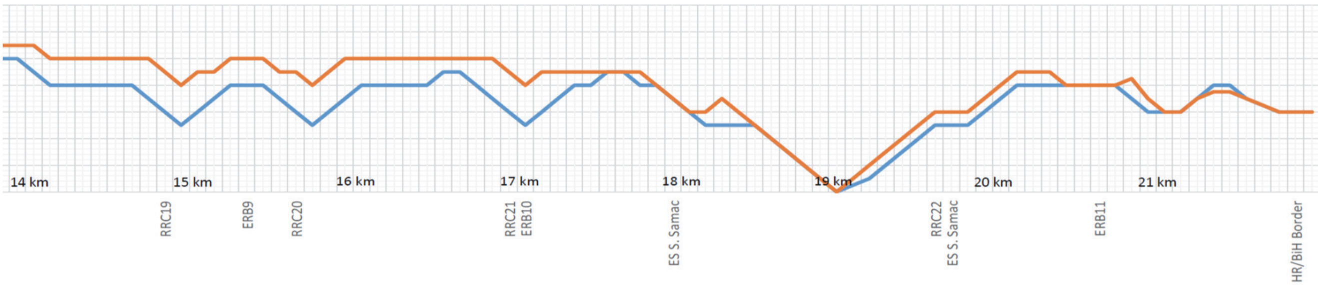

Figure 9 Train speed diagram from km 14 to km 22 on the railway: Vrpolje - State border Cro/BiH

Using expression (2), two values of railway capacity are obtained, one for the actual signalling system and the other for the same railway section but assuming that the signalling system is derived as a proposed cyber-physical model. This means that the maximum number of train pairs that can be dispatched for actual signalling system is 76 while the possible number of dispatched train pairs is increased to 96 if the proposed cyber-physical model of the signalling system is applied. A simple comparison of these values concludes that a railway capacity increase of about 20% was achieved by improving the signalling system without any interventions in the construction part or on the rolling stock.

6.2 Analysis of the Effect of the Railway Cyber-Physical Model on the Traffic Safety Segment

Railway accident statistics differentiates between five types of accidents and the sixth group is composed of uncategorized accidents. According to Eurostat data for 2016 [22] shown in the diagram in Fig. 10, it can be seen that certain types of accidents still claim a significant number of human lives.

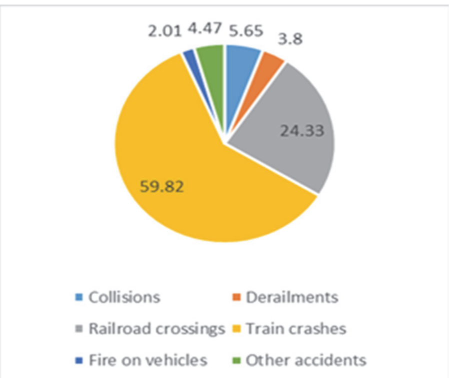

Figure 10 Railway accidents by type

By using the proposed model, it is possible to act on three types of railway accidents. Tab. 1 lists the innovations brought about by the cyber-physical model that have a direct effect on the reduction in the number of accidents by type.

Table 1 Presentation of innovations brought about by the cyber-physical model that act so as to reduce the number of accidents by type

Accident type according to Eurostat	Improvements to the cyber-physical model aimed at reducing the number of accidents
Derailments	Continuous signalling of the switch condition in the train enables a preventive reaction of the driver to the incorrect switch position. Fault signalling on the wheel bearing allows timely repairs to prevent breakdowns while running and train wheel slip.
Road crossings (including pedestrian crossings)	Continuous signalling of the railroad crossing in the train enables a preventive reaction of the driver. The signalling of a possible obstacle at the active railroad crossing enables the train to stop before a collision. Real-time signalling indicating the train approaching all road users near the railroad crossing is the information that can prevent many accidents. Simpler equipment and easier signal transmission for less frequent railroad crossings reduces the risk of collisions.
Train crashes	Real-time signalling indicating the train approaching all participants near the railway.

Based on statistical data on the number of railway accidents at an annual level from 2008 to 2017 and the said effects of the cyber-physical model on the railway signalling system, it is claimed that the application of the cyber-physical model will reduce the number of accidents in the following segments: collisions, derailments, railroad crossings and train crashes with unforeseen objects in the railway belt. Due to the fact that the model is abstract and taking into account the stochastic nature of railway accidents, the values of accident reduction for all years will be adopted linearly, as shown in Tab. 2. The data shown in Tab. 3 represent the expected percentage reductions by type from Tab. 2, which would be realized by implementing a cyber-physical model of the railway signalling system on the actual railway section.

Table 2 Estimated values of accident reduction by accident type

Accident type	Reduction / %
Derailments	15
Railroad crossings	20
Train crashes	10
Collisions	10

Algorithm for calculating total reduction for years interval form M to N is given by expression 7.

$$R[\%]=\frac{\sum_{Y=M}^{M+N}\left(A_{YT}-A_{YCP}\right)/A_{YT}}{N+M}\cdot 100 \quad (7)$$

A_{YT} – total number of accidents by year (Real s.)
A_{YCF} – total number of accidents by year (CP s.)

By applying hypothetical estimates of the reduction in the number of accidents to statistical data on the number of accidents from 2008 to 2017, new values are obtained that represent the annual number of accidents by type in the case of applying the cyber-physical model to railway signalling systems.

Statistical significance was determined by the parameter:

$$p=6,39026\cdot 10^{-7}\ll 0,05 \quad (6)$$

Parameter p is a result of the t-test applied to the aforementioned statistical data. Since the parameter value is much less than 0.05, this means that a statistically significant reduction in the number of accidents was achieved by applying the model. The actual values of accidents and reduced values of accidents achieved by applying the cyber-physical model to the signalling system of the railway are shown in Tab. 3 by years.

Table 3 Comparative presentation of the number of accidents of actual signalling systems and the application of a hypothetical cyber-physical model of signalling systems to European railways

Year	2008	2009	2010	2011	2012
Total number of accidents (real system)	4,124	3,208	2,694	2,585	2,393
Total number of accidents (CP model)	3,603	2,827	2,369	2,276	2,094
Difference	521	381	325	309	299
Year	2013	2014	2015	2016	2017
Total number of accidents (real system)	2,250	2,355	2,080	2,089	2,013
Total number of accidents (CP model)	1,969	2,064	1,821	1,837	1,762
Difference	281	291	259	252	251

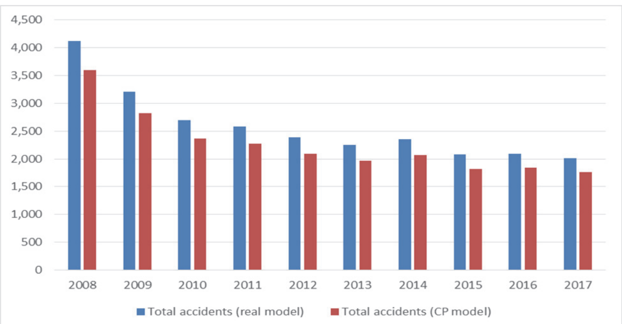

Figure 11 Comparison diagram of the statistically real number of accidents and the number of accidents by a hypothetical application of the cyber-physical model of signalling systems to European railways

A graphical representation of the results from Tab. 3 is given in Fig. 11.

It is obvious from the diagram that in each year in the period from 2008 to 2017, assuming that the cyber-physical model was technically implemented each year, the number of accidents would have been numerically lower than the actual number. In addition to this statistical significance, this is also important from the perspective of human safety, because a decrease in the number of accidents reduces the risk of injuries and deaths for road users.

6.3 Analysis of the Effect of the Railway Cyber-Physical Model on the Traffic Safety Segment

The availability parameter of a particular element is defined as its ability to be able to perform the required operation in a given time [23]. The availability value ranges from 0 to 1, with value 1 determining a 100% probability that the element will be available. The basic targets for European railways are to shift 50% of road traffic to rail and achieve a 60% reduction in CO_2 emissions by 2050, [24]. This implies a significant increase in railway capacity through well-developed system development and maintenance strategies. The basis for developing these strategies are credible data on breakdowns, train delays, and train accuracy.

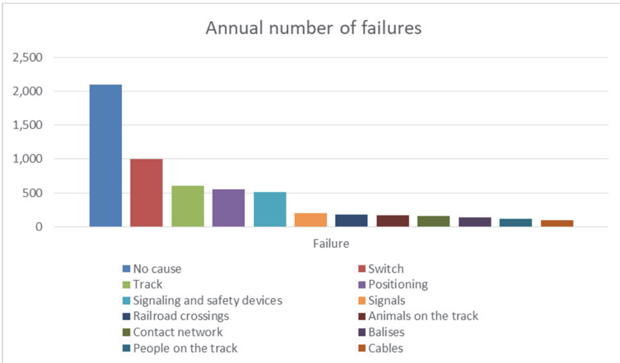

Figure 12 Annual number of failures by type of failure

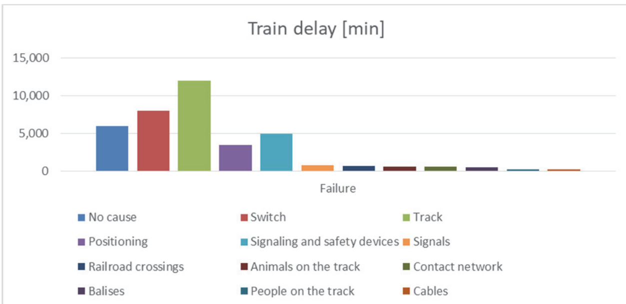

Figure 13 Train delay depending on the type of failure

Data on corrective railway maintenance or breakdowns and their consequences in the form of train delays were taken from the document on measuring and monitoring the operational railway infrastructure availability in Sweden [25]. The total number of breakdowns is 24,816, 25% of which resulted in train delays. Data are divided by type of failure, i.e. the actual part of the railway system where the failure occurred (switch, track, positioning, signalling devices, signals, railroad crossings, animals on the track, contact network, balise or failures for which no cause has been established). Data on breakdowns for 2013 are shown in the diagram in Fig. 12.

Fig. 13 shows train delays in minutes caused by a specific type of failure.

The cyber-physical model of the railway in the maintenance segment enables replacement of corrective maintenance actions after a breakdown event with preventive maintenance actions, whereby in most cases an adverse event is prevented [26]. It can be seen from the diagram in Fig. 13 that certain types of failures lead to a total train delay of over a few hundred hours per year. By improving the device fault interface in the field, it is possible to obtain real-time information about the condition, disturbance or fault, whereby the unwanted event is localized faster and easier. In certain cases, this enables preventive troubleshooting in the period when trains do not run, thus avoiding train delays [27]. If a malfunction occurs while driving, its localization is facilitated while reducing the mean time between repairs (MTTR). The construction of a detailed database of failures and disturbances reduces the number of unknown failures, while the frequent case of train downtime in which no failures are found is reduced, which also represents an improvement in the maintenance process [28].

7 CONCLUSION

The contribution of the developed cyber-physical model of the railway signalling system from the aspect of improving traffic safety is reflected in the new possibilities of acting on critical points in the system (road crossings, signalling elements on the track and vital elements on the train). In this way, real-time information on the state of the system in the train, control centre and other traffic participants is available for road crossings, which might prevent many accidents, because all participants can react in a timely manner, which significantly reduces unforeseen situations. Model simulation has shown that it is feasible to programmatically describe all the actions of the upgraded equipment in the physical layer and thus create a realistic and reliable copy of the actual process state. Statistical analysis shows that the application of the model achieves a statistically significant reduction in the number of accidents. The proposed system enables layered investment in the construction of a cyber-physical model, which in fact represents the implementation of the system in phases with the upgrading principles. The new model can also increase rail efficiency and passenger comfort as it is possible to achieve a higher train speed and thus higher rail efficiency. The cyber-physical model brings a major shift in terms of system maintenance procedures, which is crucial to increase security and reduce costs. This turn is reflected in a significant improvement in relation to the detection of device failures in the railway system and the identification of a wide range of failures in real time. This significantly reduces corrective actions in maintenance, and the number of preventive actions is reduced to the optimal measure according to actual needs. Such an approach reduces maintenance costs as well as unwanted traffic jams that always bring unpredictable losses.

Future research is needed in the areas of testing and selecting optimal wireless networks for signal transmission between track equipment, train and control Centre. It is also necessary to prepare detailed technical studies that will determine interventions and modifications of the equipment in the physical layer of the railway, which must be based on a specific section and equipment on which the implementation of its cyber-physical model is planned. In the end, a wide field of dedicated software solutions, data analysis and processing as well as various visualization interfaces remain to be addressed in future research.

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